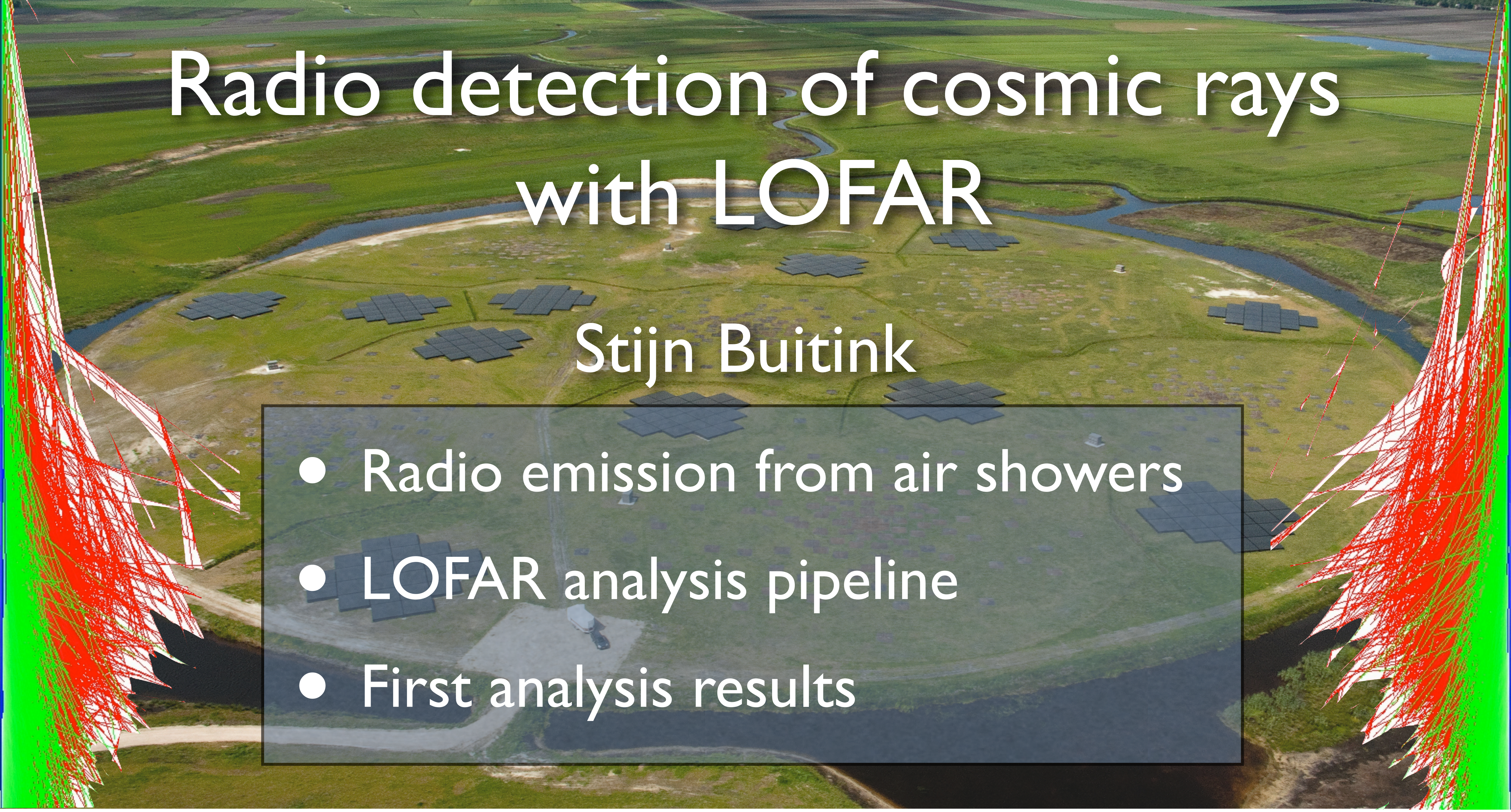
Radio detection of cosmic rays with LOFAR

Stijn Buitink

- Radio emission from air showers
- LOFAR analysis pipeline
- First analysis results

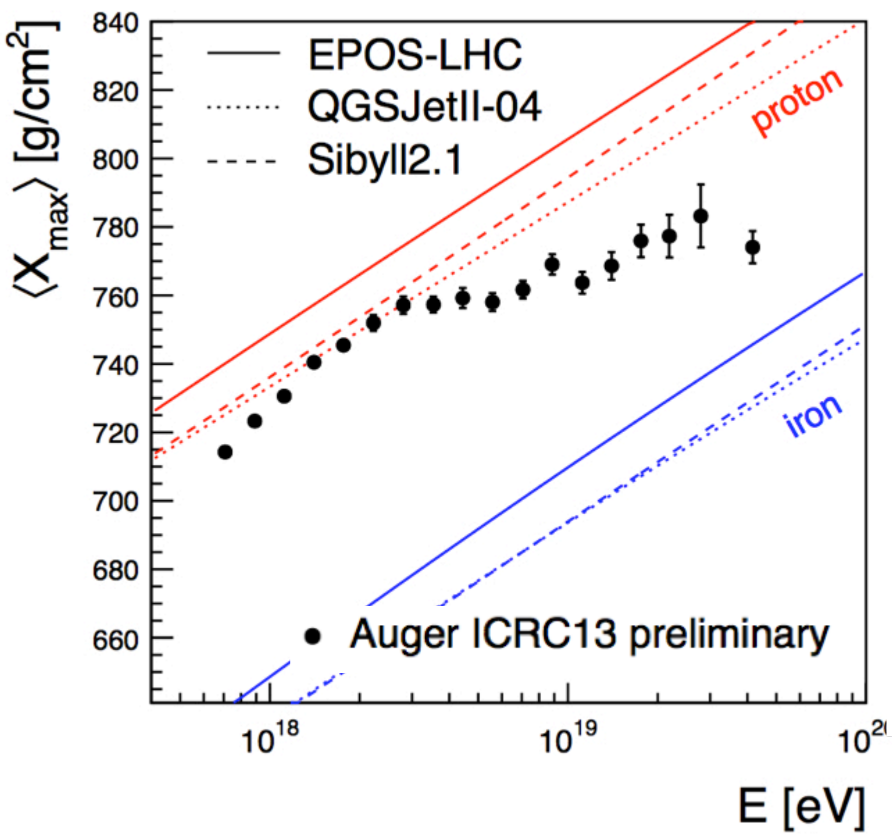


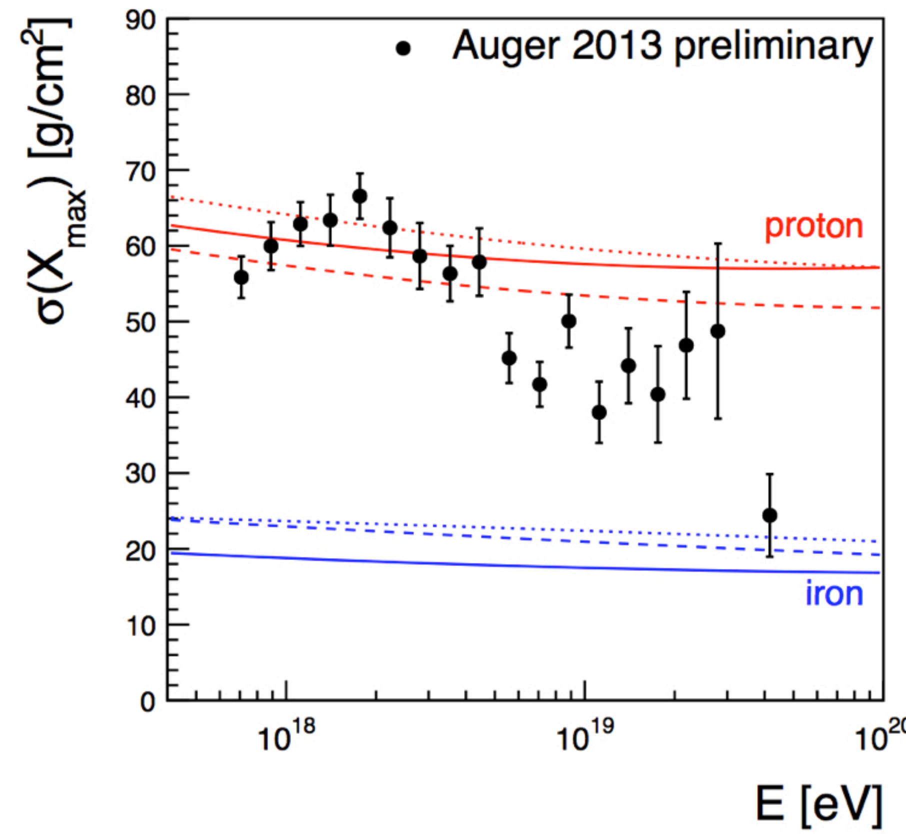
A. Corstanje, J.E. Enriquez, H. Falcke, W. Frieswijk, J. Hörandel, T. Huege, M. Krause, A. Nelles, P. Schellart, O. Scholten, S. Thoudam, S. ter Veen, M. van den Akker

for the LOFAR collaboration

LOFAR Radboud Universiteit Nijmegen KVI university of groningen NWO

Radio: a new handle on CR Composition



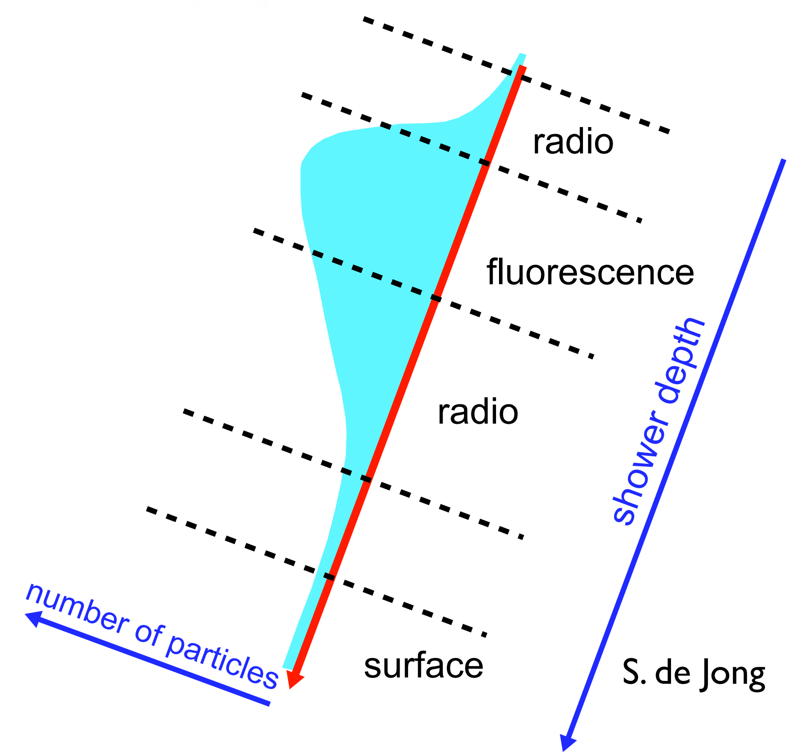


Auger ICRC 2013 Rio de Janeiro

Surface detection: muon component
- very sensitive to hadronic interaction models

Fluorescence Detection to measure Xmax
- duty cycle ~10%, σ ~ 20 g/cm^2

Radio Detection to measure Xmax:
- cheap detectors, duty cycle ~100%
- attractive method to increase statistics at ultra-high energy!



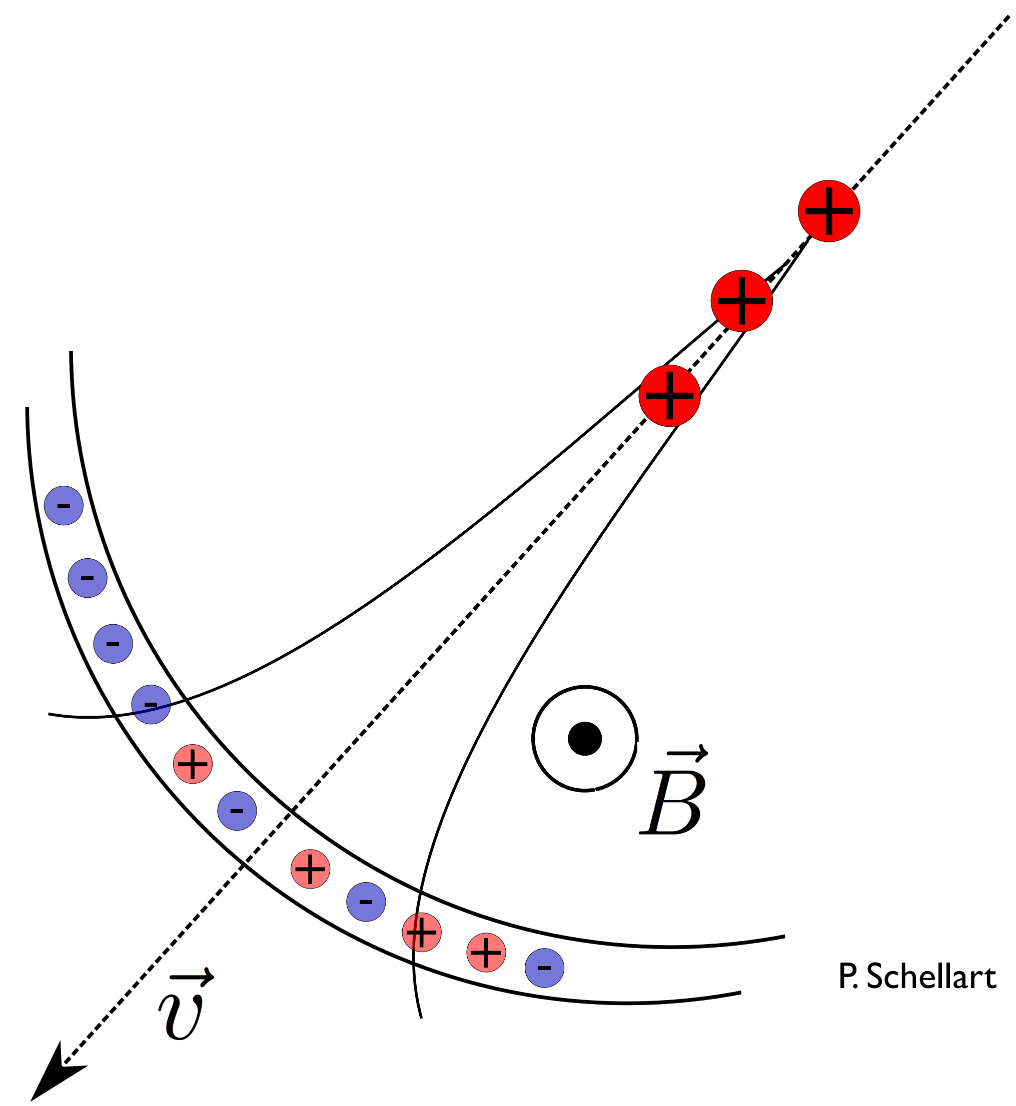
Does it work? Is the precision good enough?

What drives the radio emission?

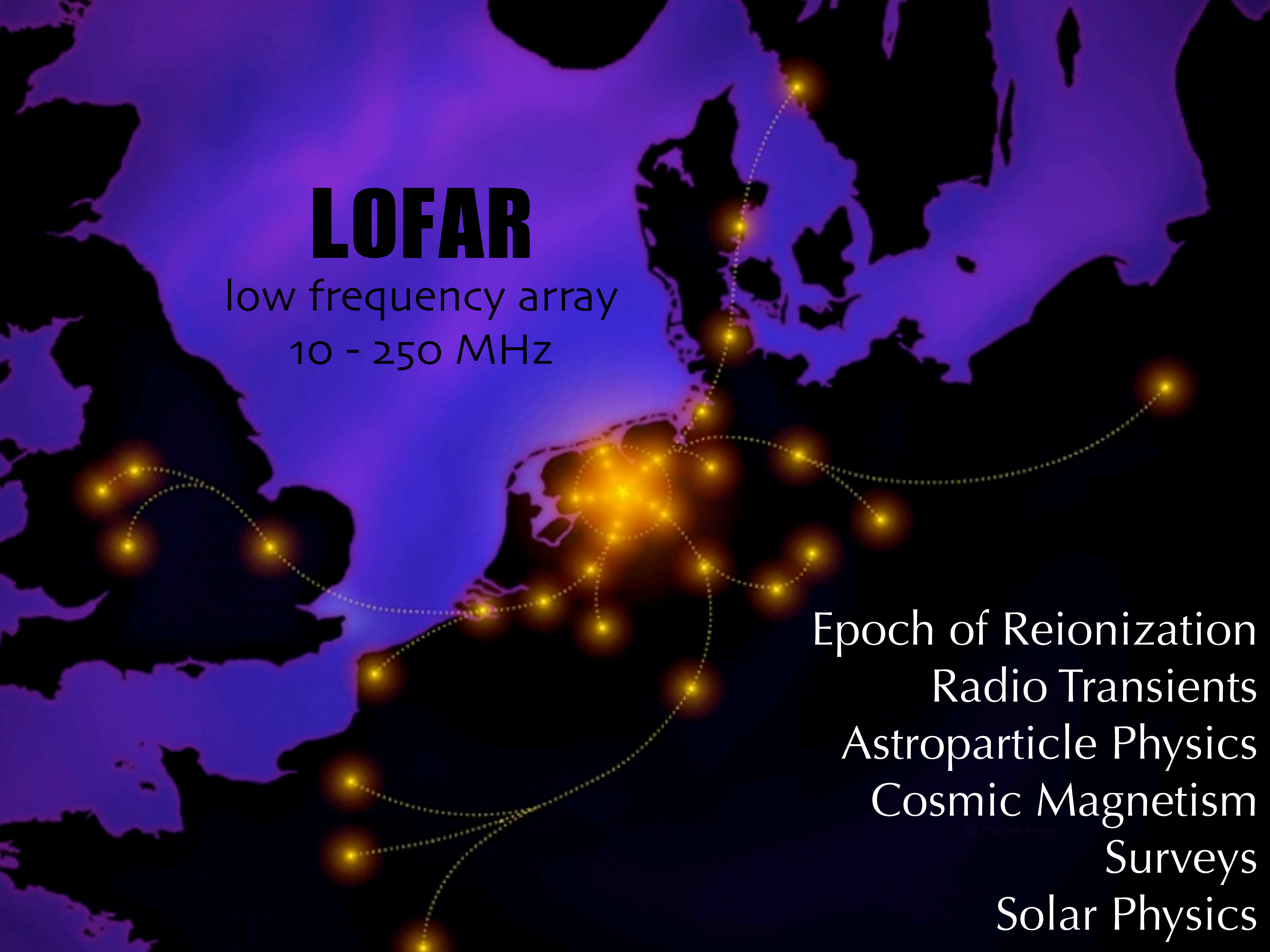
- <u>Earth magnetic field</u>
  electrons/positrons deflected
  $E \sim dn_{ch}/dt$

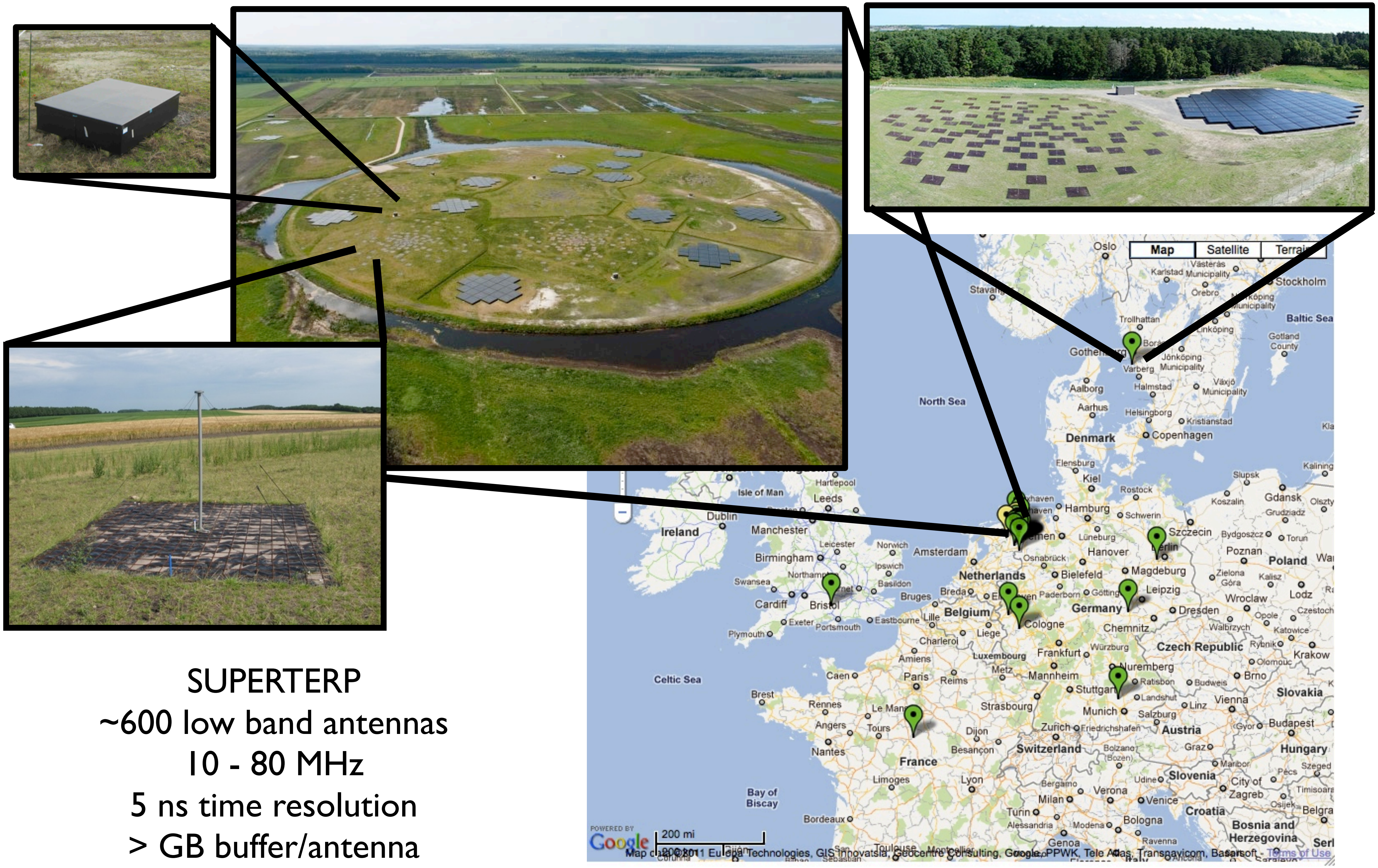
- <u>Charge excess</u>
  negative charge due to electron knockouts
  $E \sim d(n_e - n_p)/dt$

- <u>Non-unity index of refraction</u>
  Cherenkov-like effects
  ring structure possible



Coherent at 100 MHz
wavelength > shower front size
$P \sim n^2$


LOFAR
low frequency array
10 - 250 MHz
Epoch of Reionization
Radio Transients
Astroparticle Physics
Cosmic Magnetism
Surveys
Solar Physics



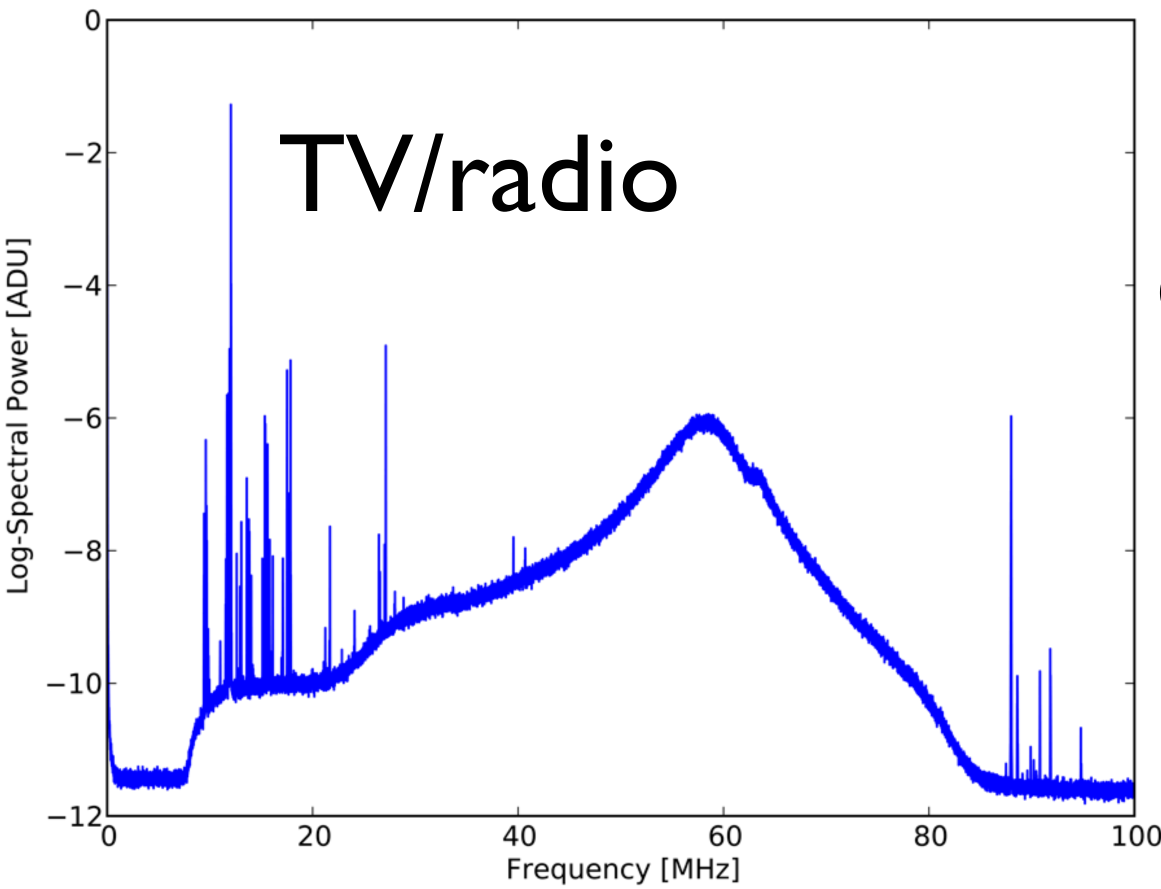
SUPERTERP
~600 low band antennas
10 - 80 MHz
5 ns time resolution
> GB buffer/antenna

+ LORA
LOFAR Radboud air shower array
20 scintillator stations (ex-KASCADE)

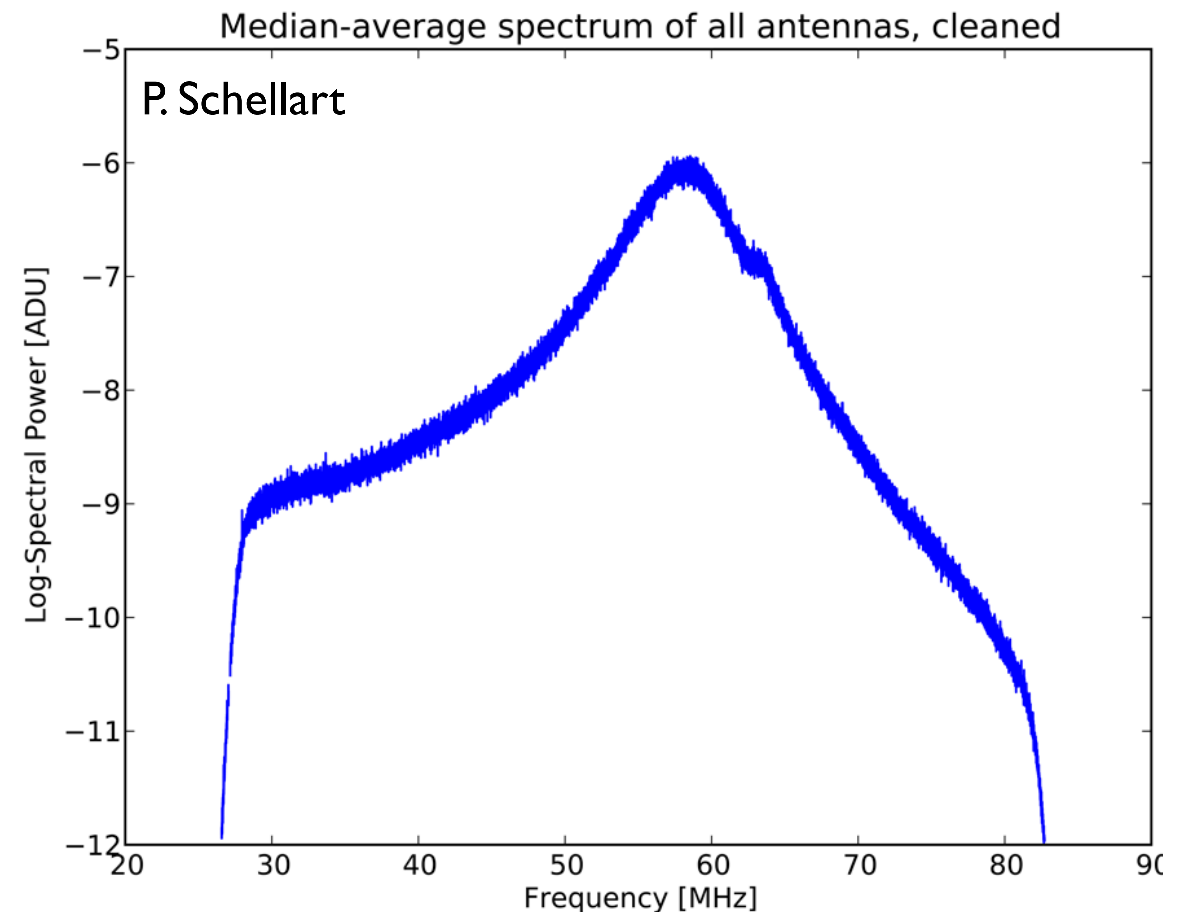
24 core stations
9 remote stations
8 international stations

Reconstruction pipeline

1. LORA scintillators provide trigger & shower reco

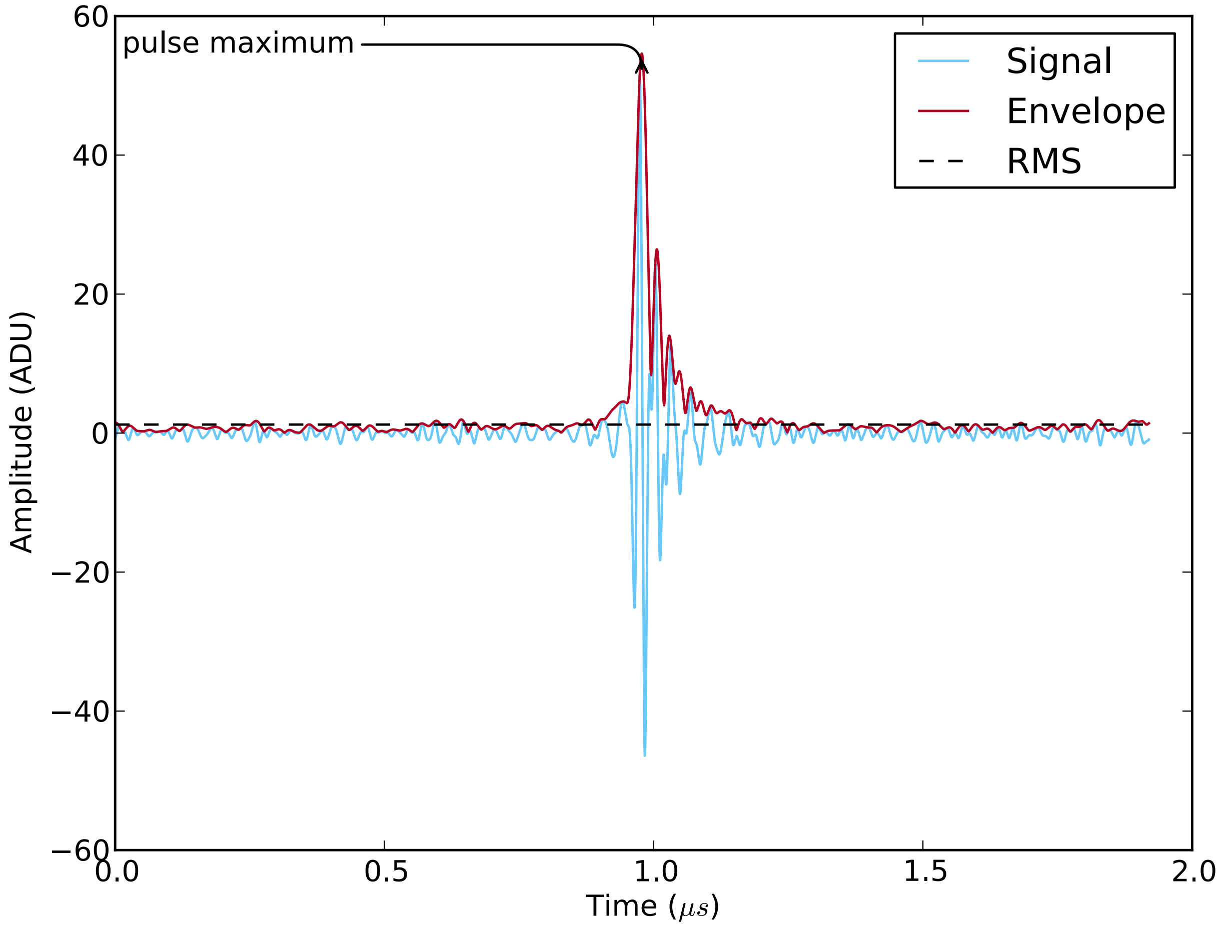


cleaning →

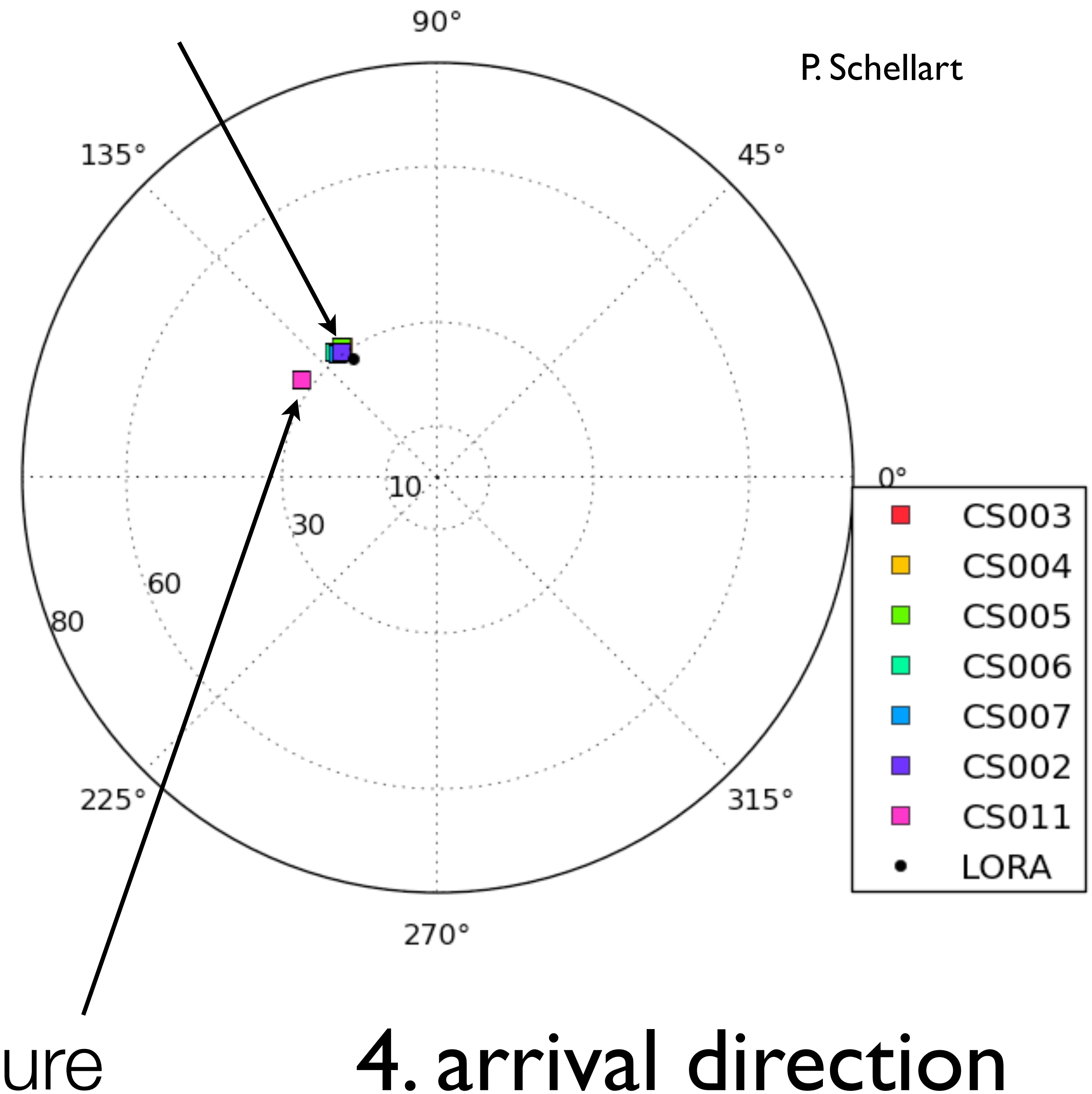


2. RFI cleaning using phase stability of emitters

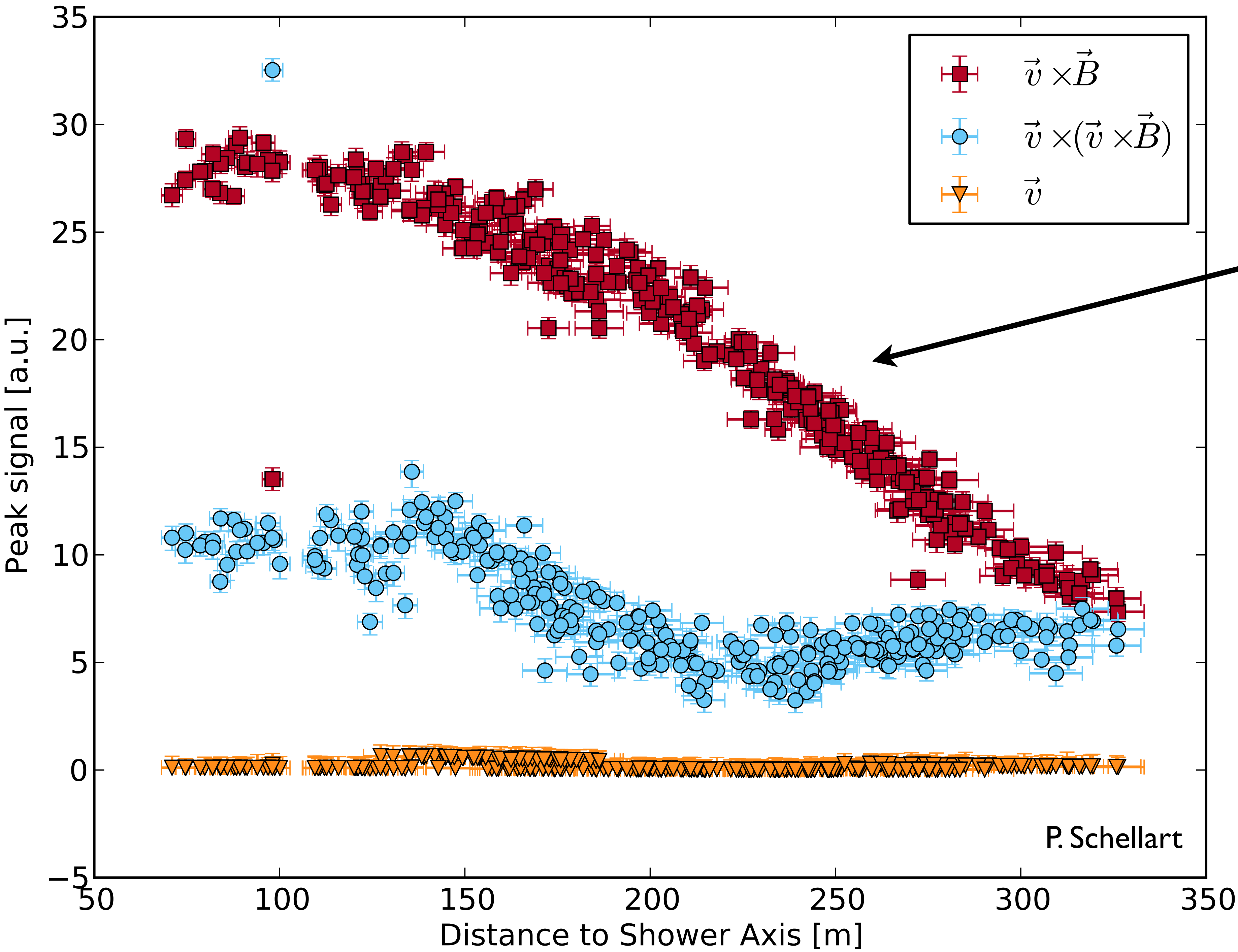
Particle Detector & Radio Agree



3. pulse finding



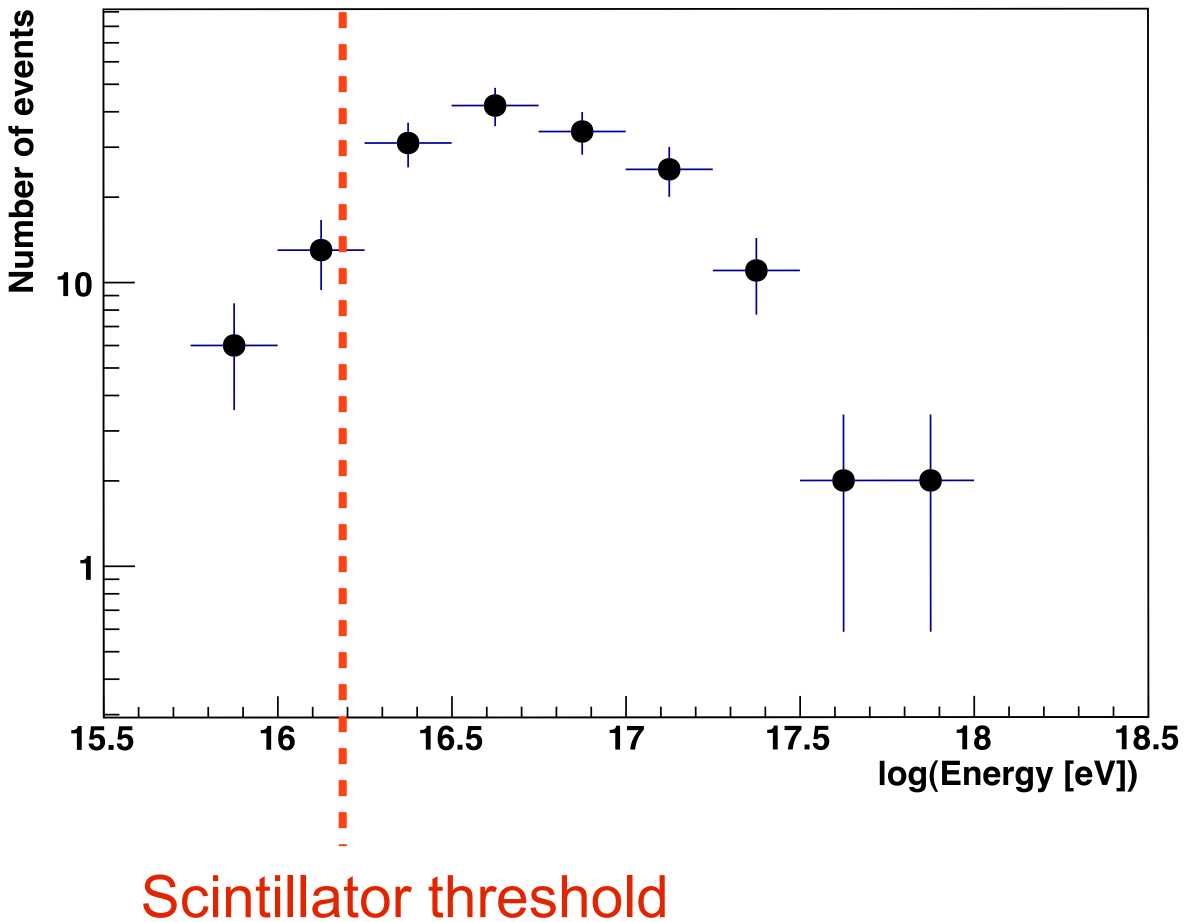
4. arrival direction fit



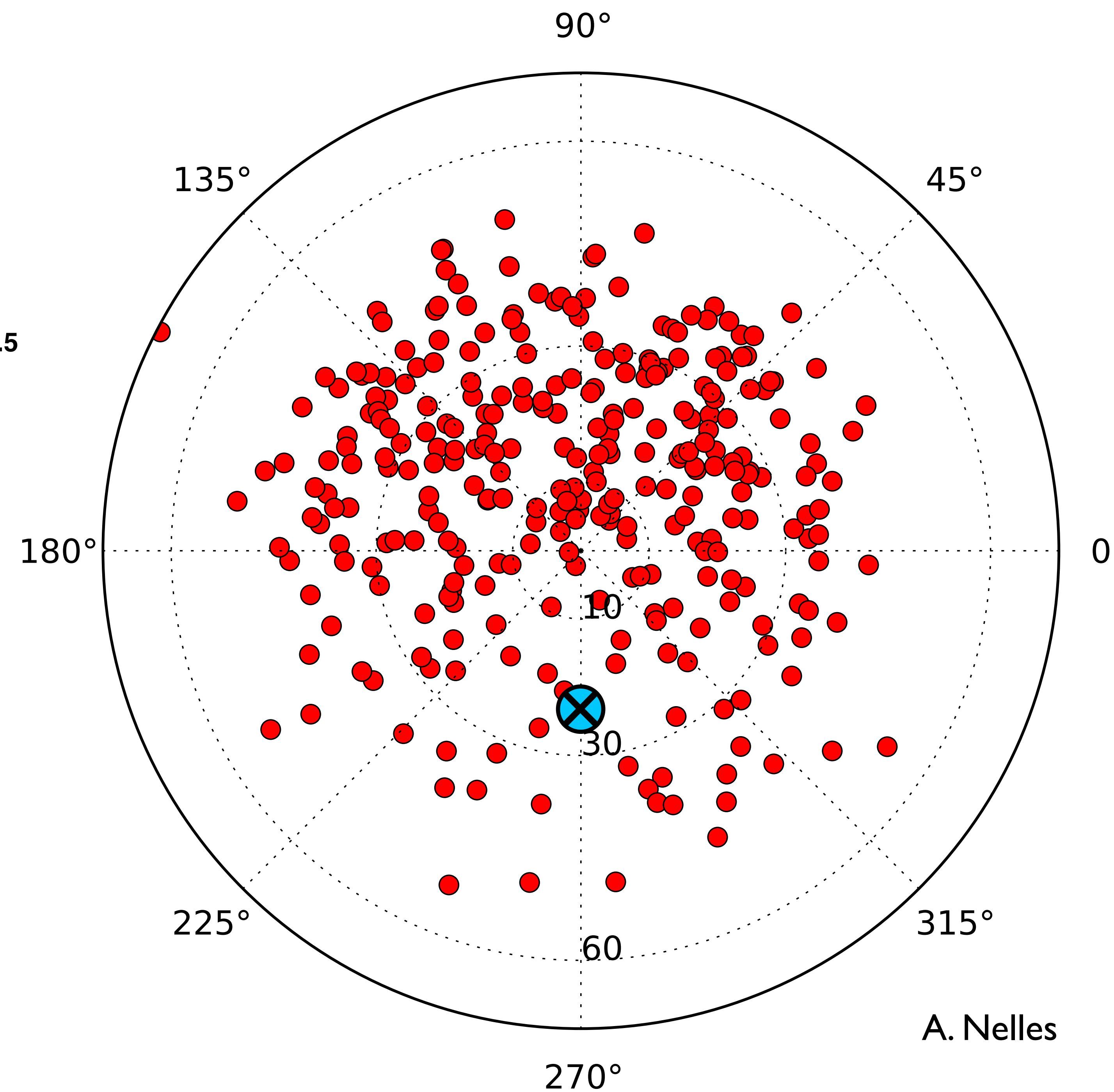
Geomagnetic = dominant

5. Apply antenna model to get LDF

Air Showers at 30 - 80 MHz



sample of 400+ showers

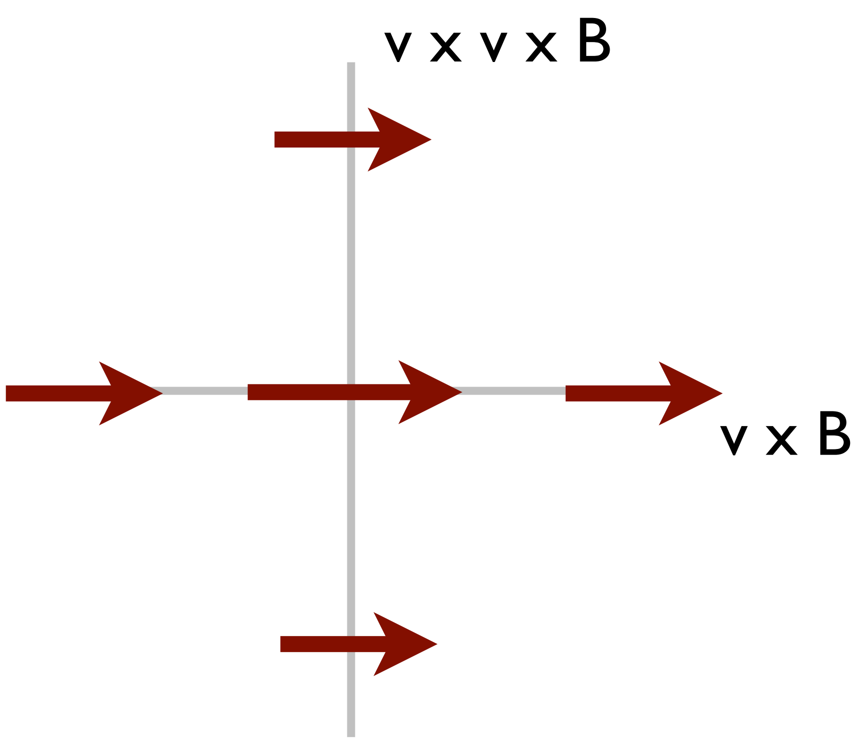


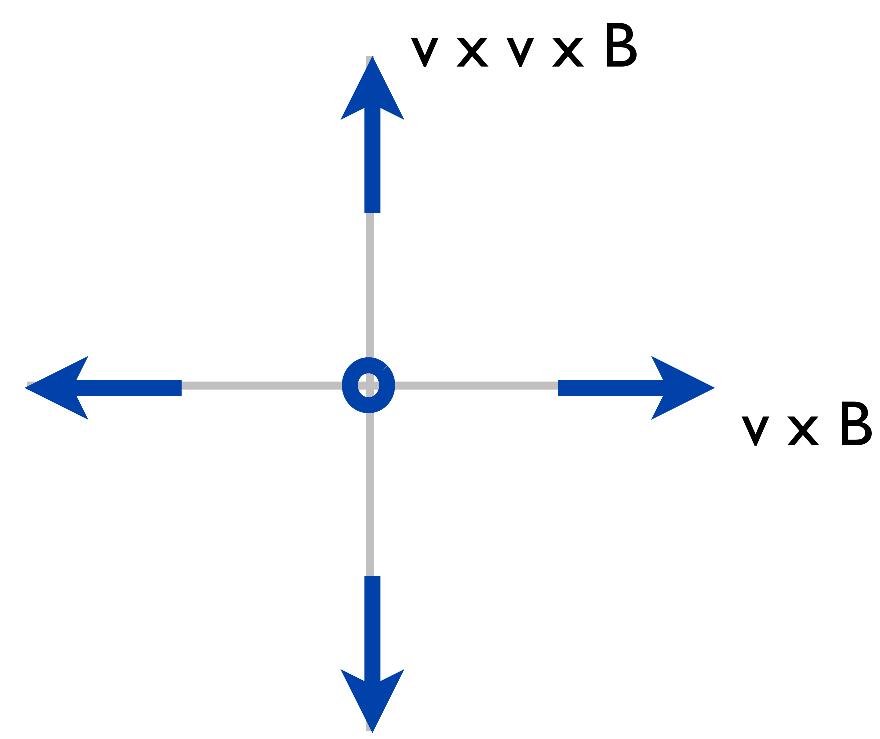
range $10^{16.5}$ - $10^{18.5}$ eV

north-south asymmetry

Xmax measurement by fitting lateral distribution of P

radio pattern

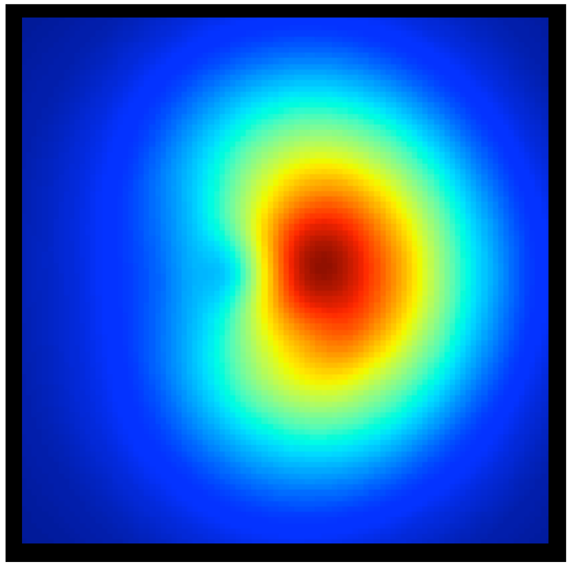




vector sum of geomagnetic and charge excess component

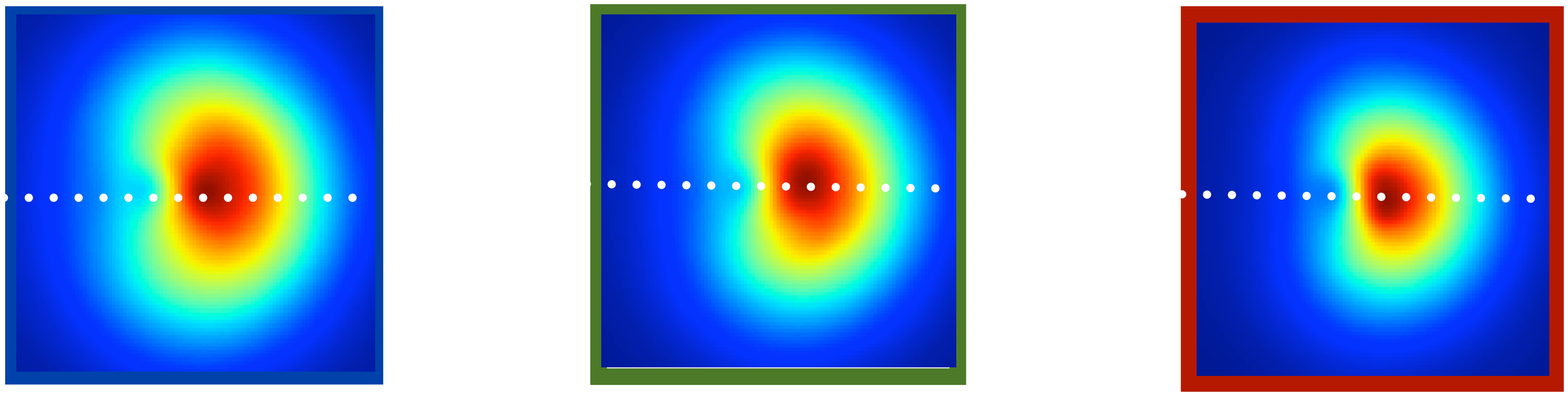
relativistic beaming

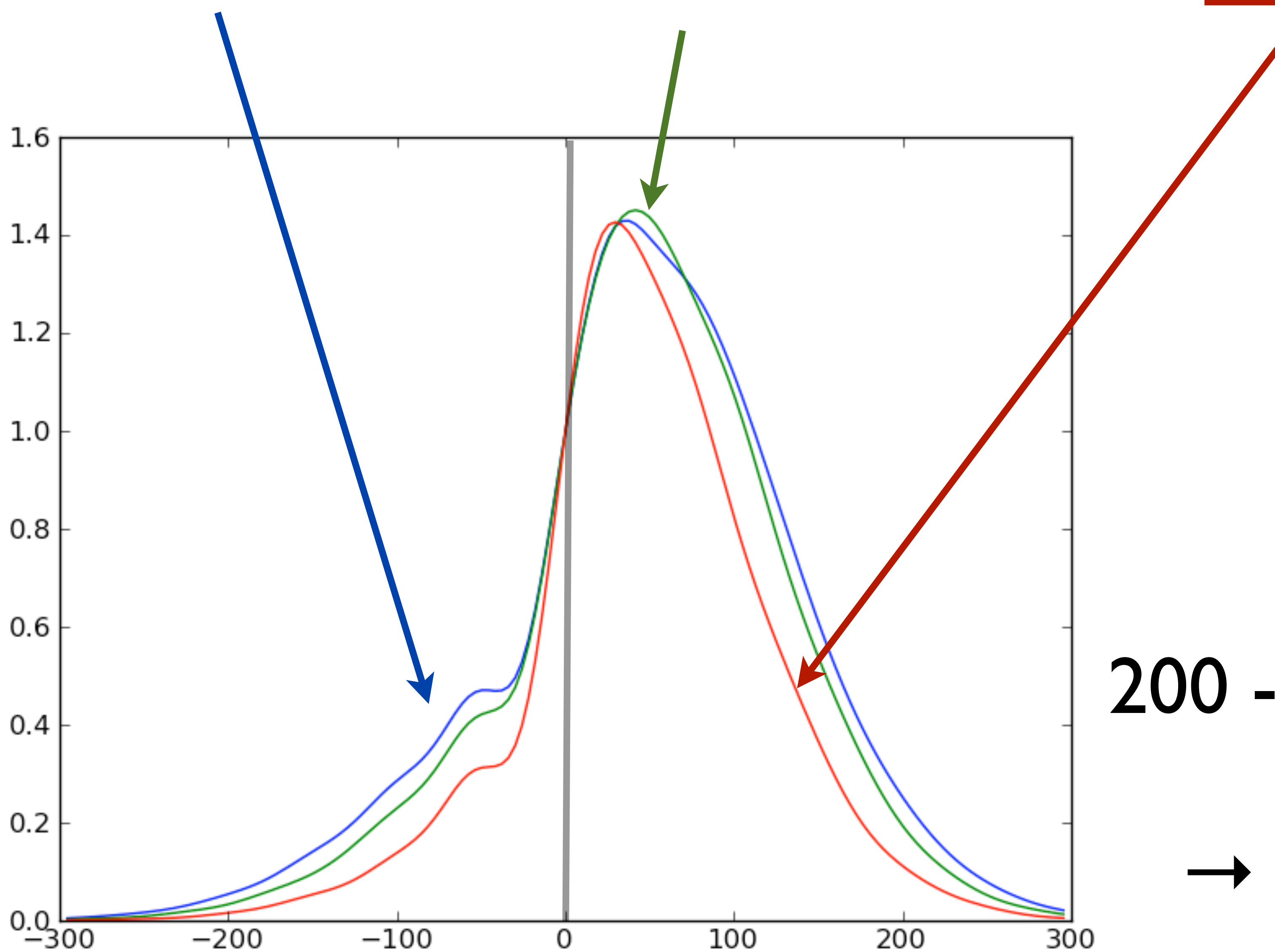
distortion by Cherenkov-like effects (n≠1)



CoREAS simulation

X_{max} ~ 600 g/cm^2 X_{max} ~ 650 g/cm^2 X_{max} ~ 700 g/cm^2



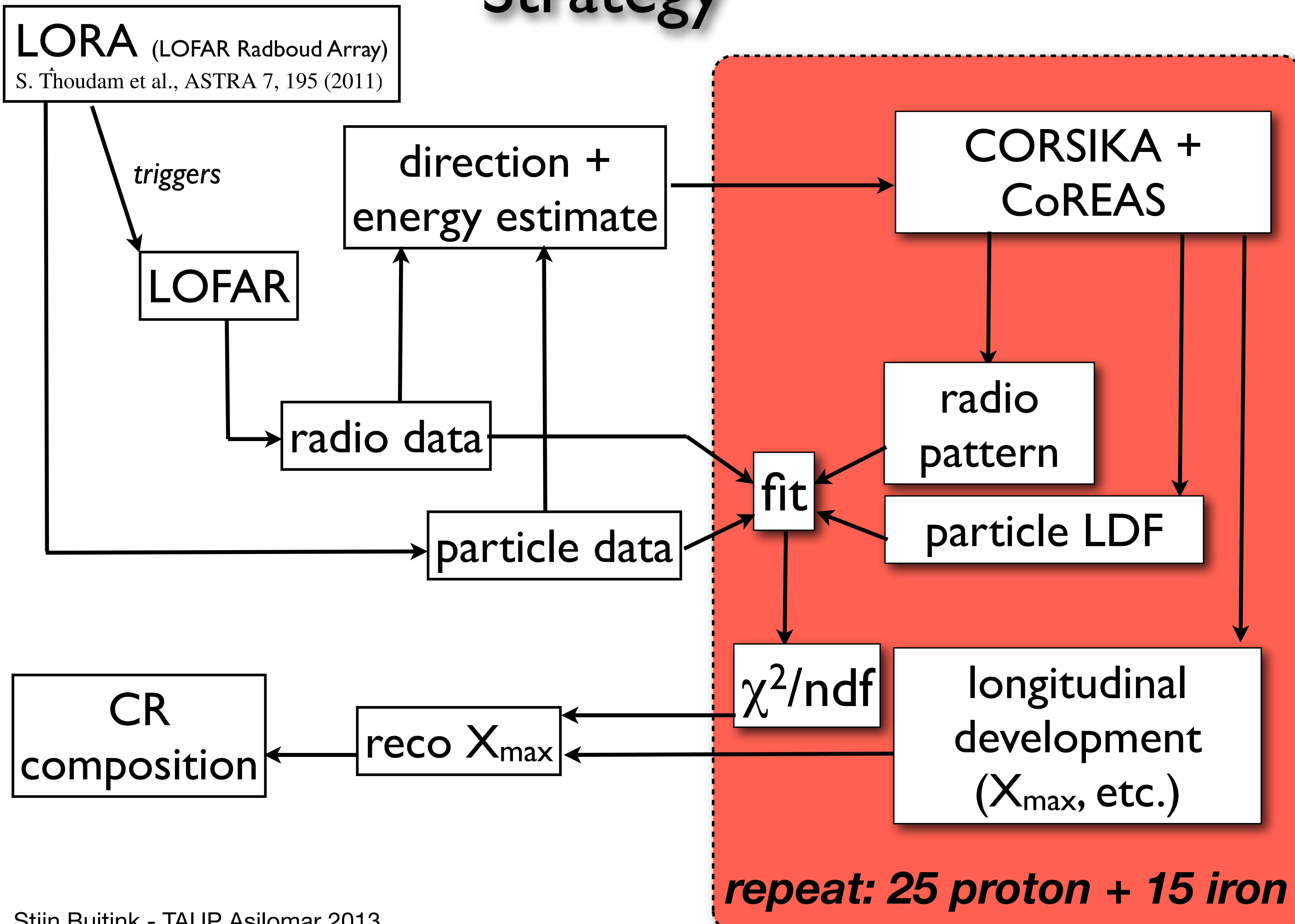


cross section along v x B

LOFAR:
200 - 400 antennas/event

→ *fit full 2D pattern !*

Strategy



LORA (LOFAR Radboud Array)
S. Thoudam et al., ASTRA 7, 195 (2011)
triggers
LOFAR
direction + energy estimate
radio data
particle data
CORSIKA + CoREAS
radio pattern
particle LDF
fit
χ^2/ndf
longitudinal development (X_{max}, etc.)
reco X_{max}
CR composition
repeat: 25 proton + 15 iron

Fit for each simulation

Minimize χ^2 of radio and particle data simultaneously

$$\chi^2 = \sum_{antennas} \left(\frac{P_{ant} - \boxed{f_r} P_{sim}(x_{ant} + \boxed{x_{off}}, y_{ant} + \boxed{y_{off}})}{\sigma_{ant}} \right)^2$$

$$+ \sum_{detectors} \left(\frac{d_{det} - \boxed{f_p} d_{sim}(x_{det} + \boxed{x_{off}}, y_{det} + \boxed{y_{off}})}{\sigma_{det}} \right)^2$$

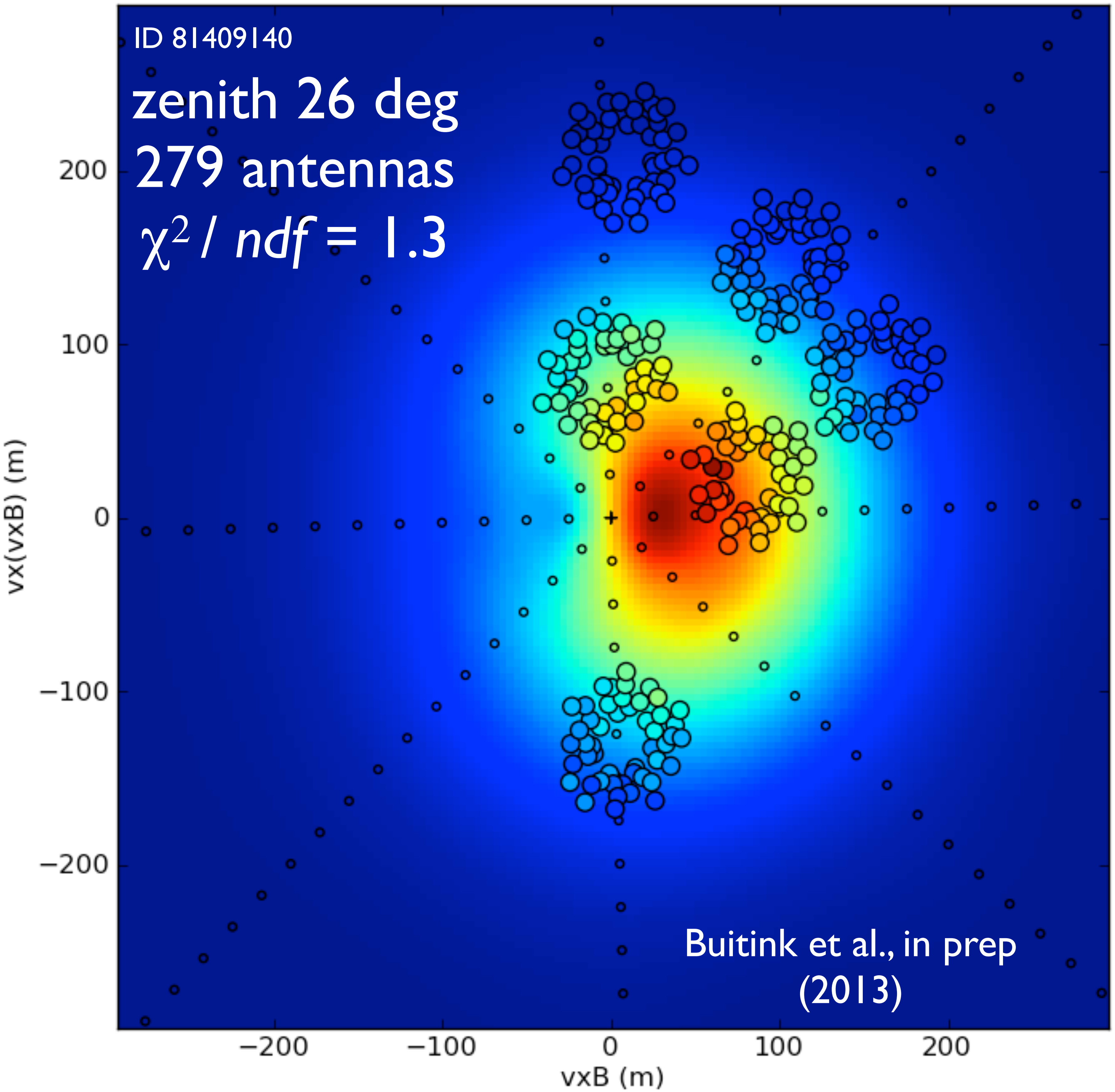
4 fit parameters:

core position

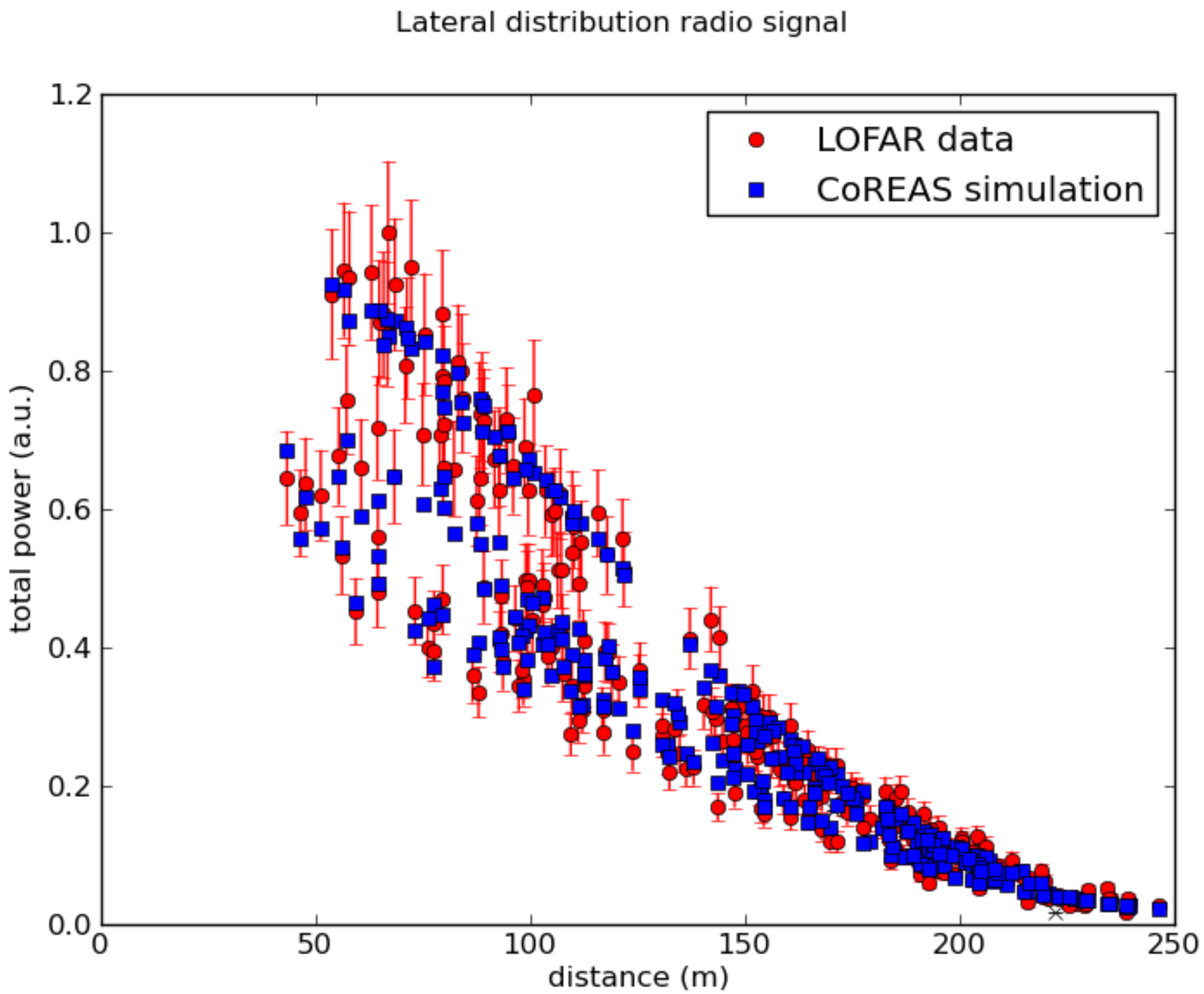
radio power scale factor

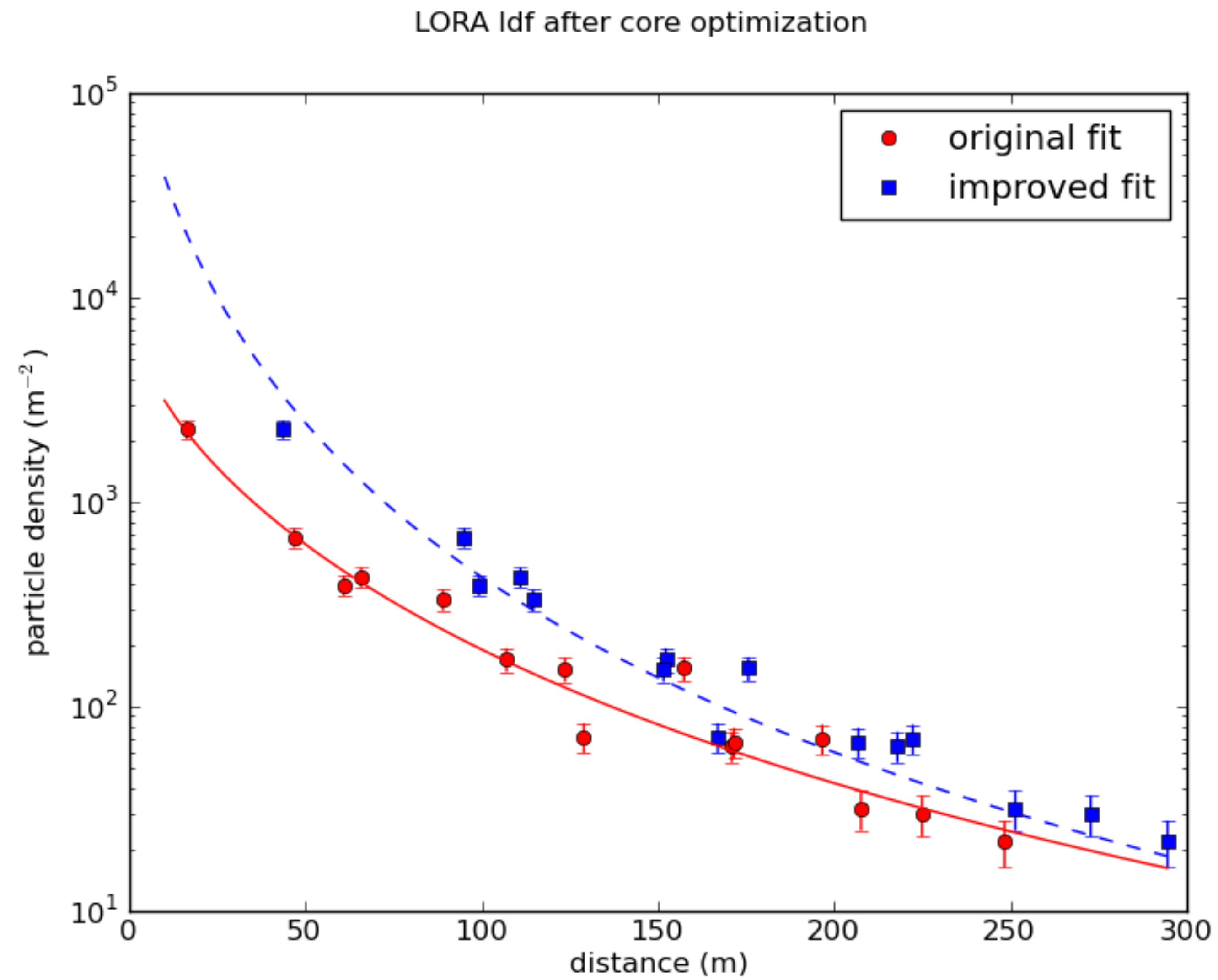
particle density scale factor

best fit out of 40 simulations



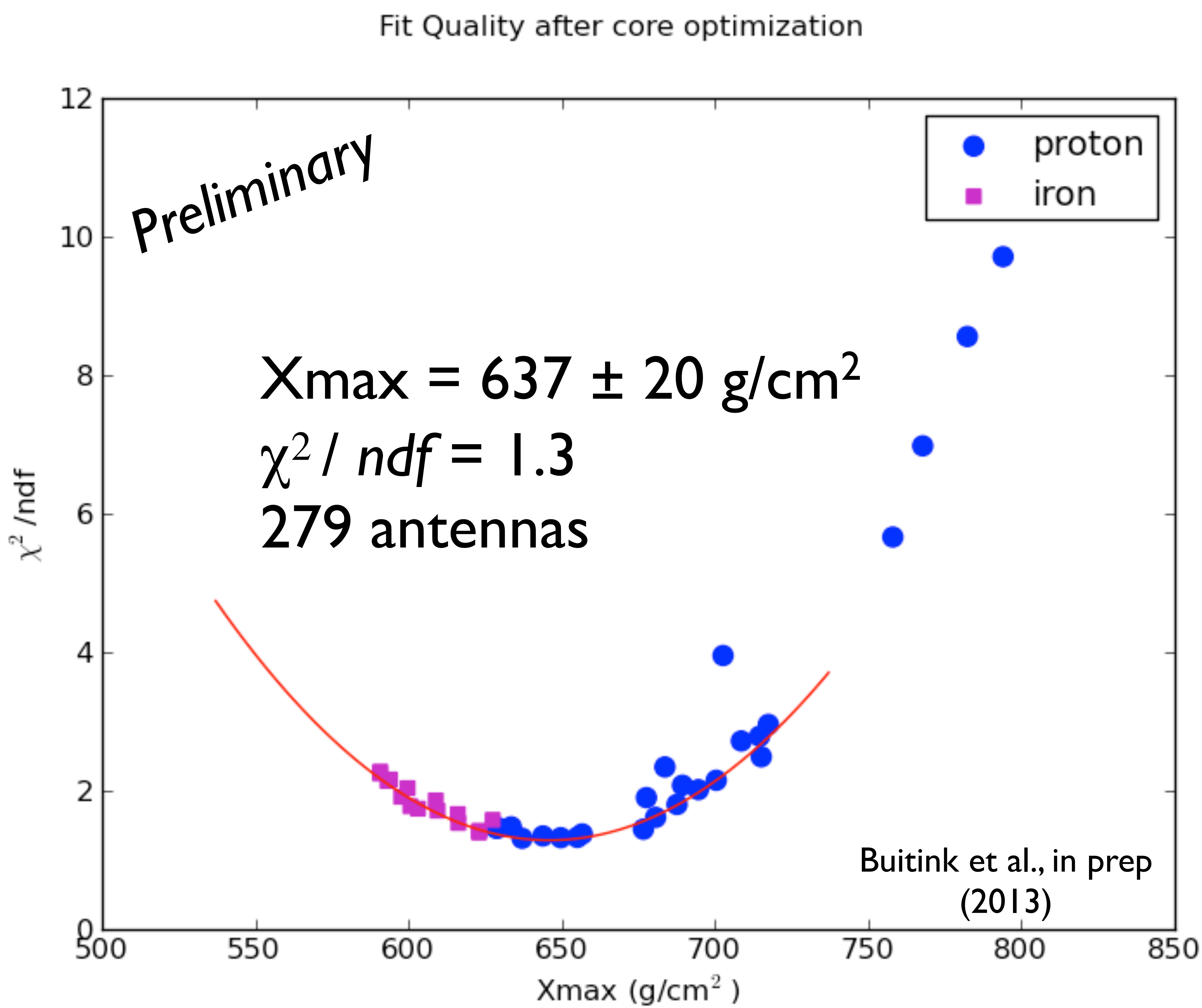
best fit out of 40 simulations





1D LDFs don't fit !

- core shifted by ~ 50m
- revised energy estimate


Fit Quality after core optimization
Preliminary
proton
iron
Xmax = 637 ± 20 g/cm²
χ² / ndf = 1.3
279 antennas
Buitink et al., in prep (2013)
χ² /ndf
Xmax (g/cm²)
0
2
4
6
8
10
12
500
550
600
650
700
750
800
850

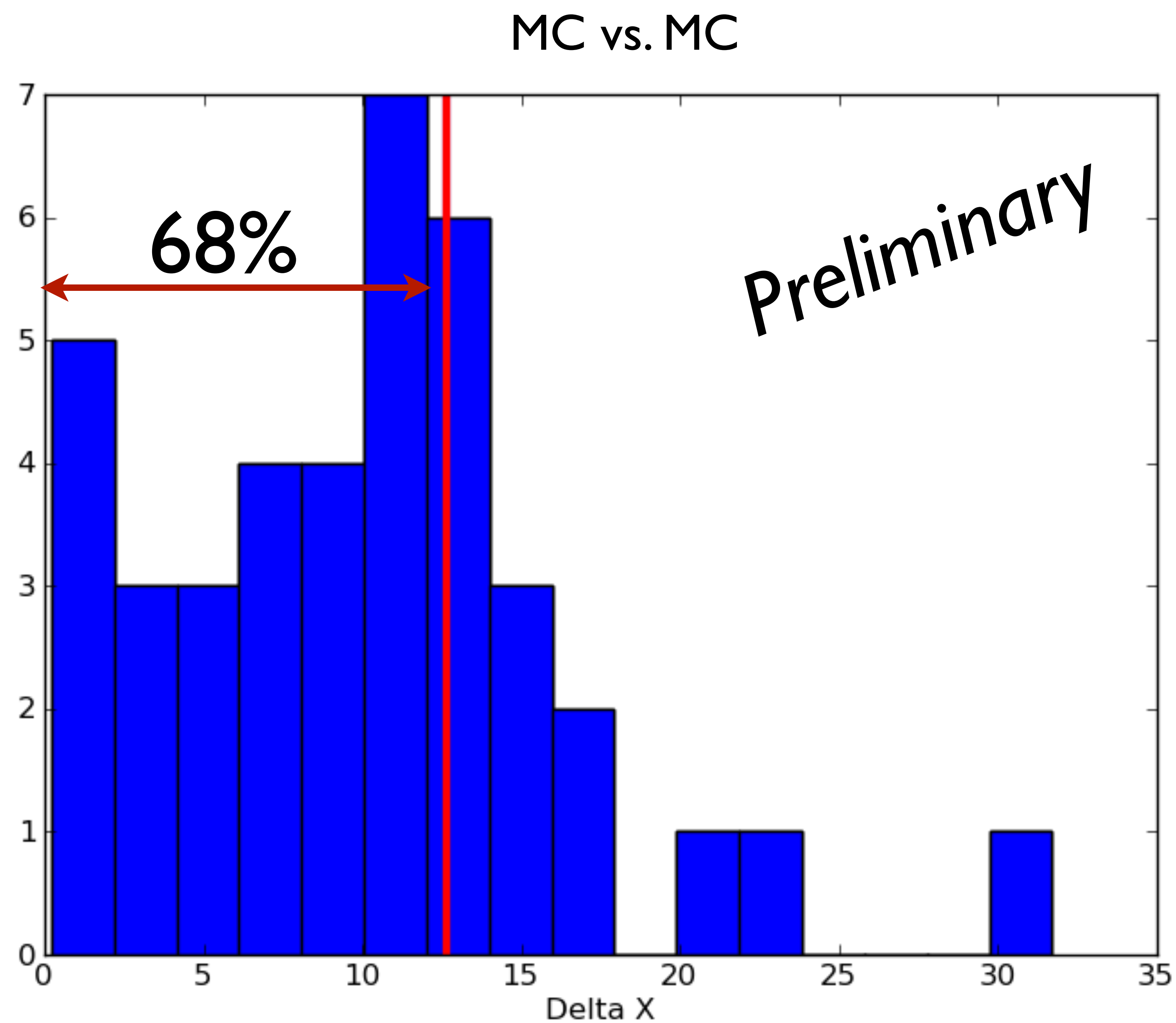
Errors

<u>Procedure</u>:
- single out 1 sim
- add noise
- reconstruct with other 39 sims
- calculate error ΔX

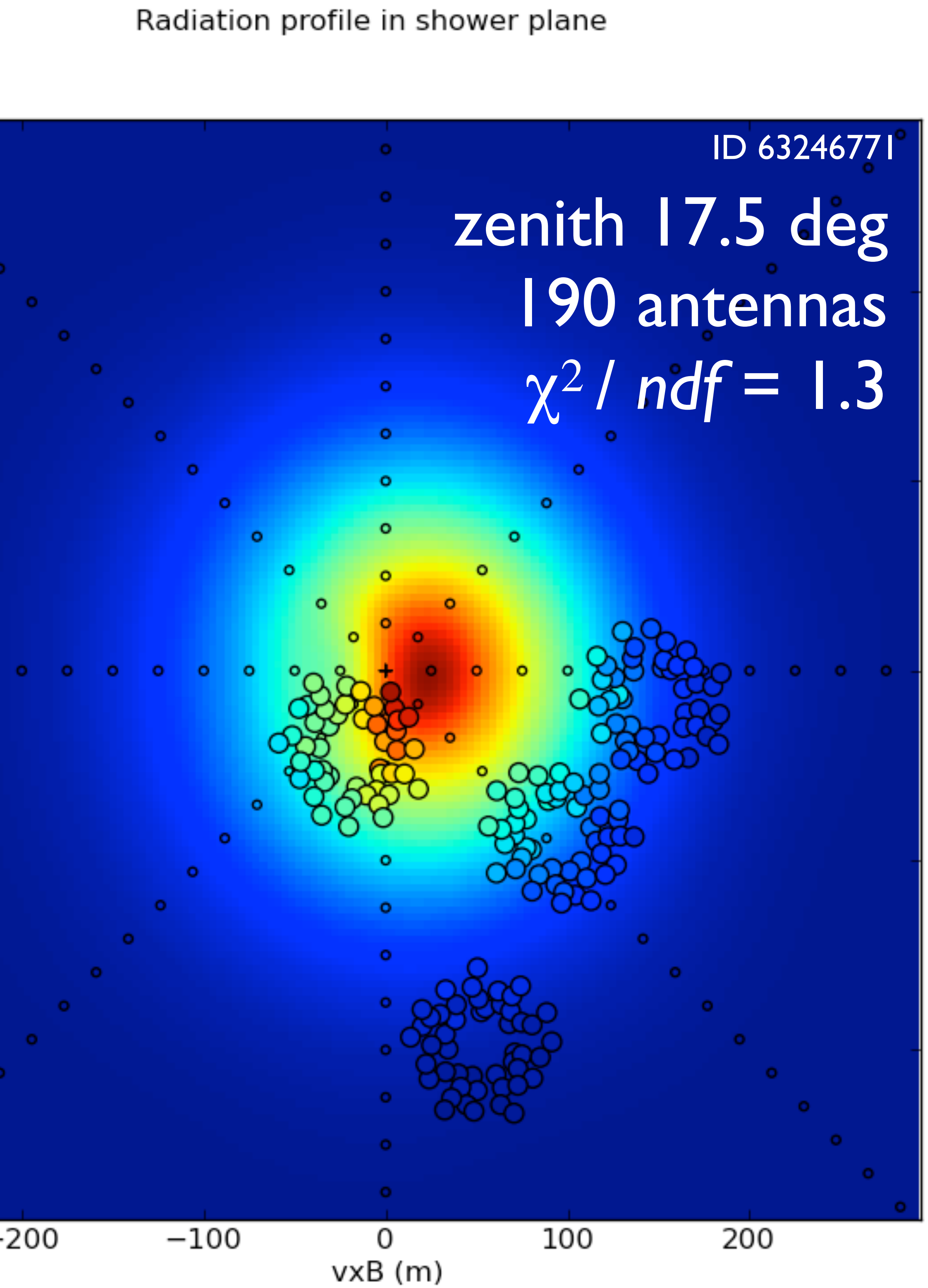
repeat for all sims

construct region that contains 68% of ΔX

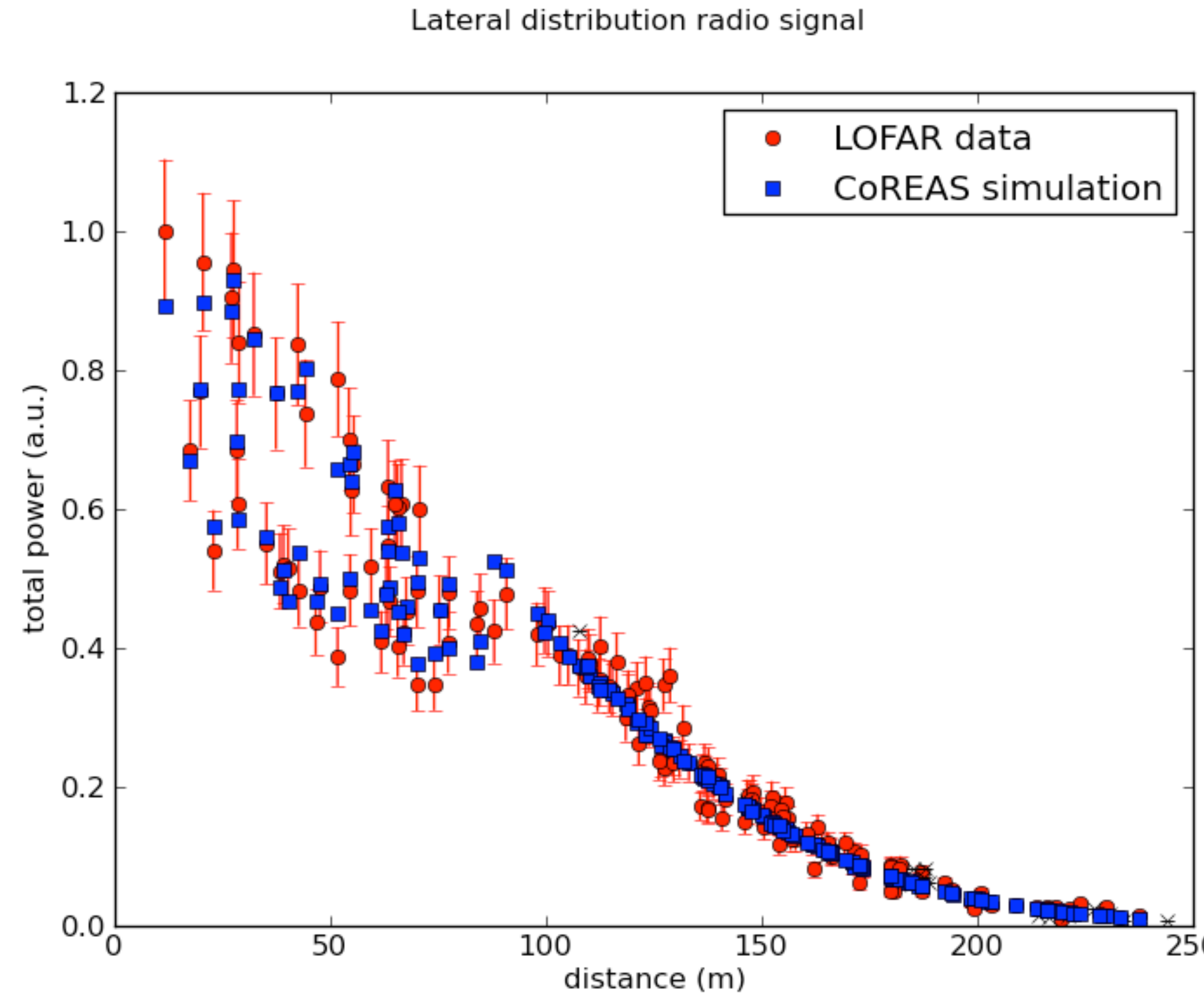
$\sigma_{meth} = 12.7\ g/cm^2$
$\sigma_{atm} = 15\ g/cm^2$
$\sigma = 19.6\ g/cm^2$



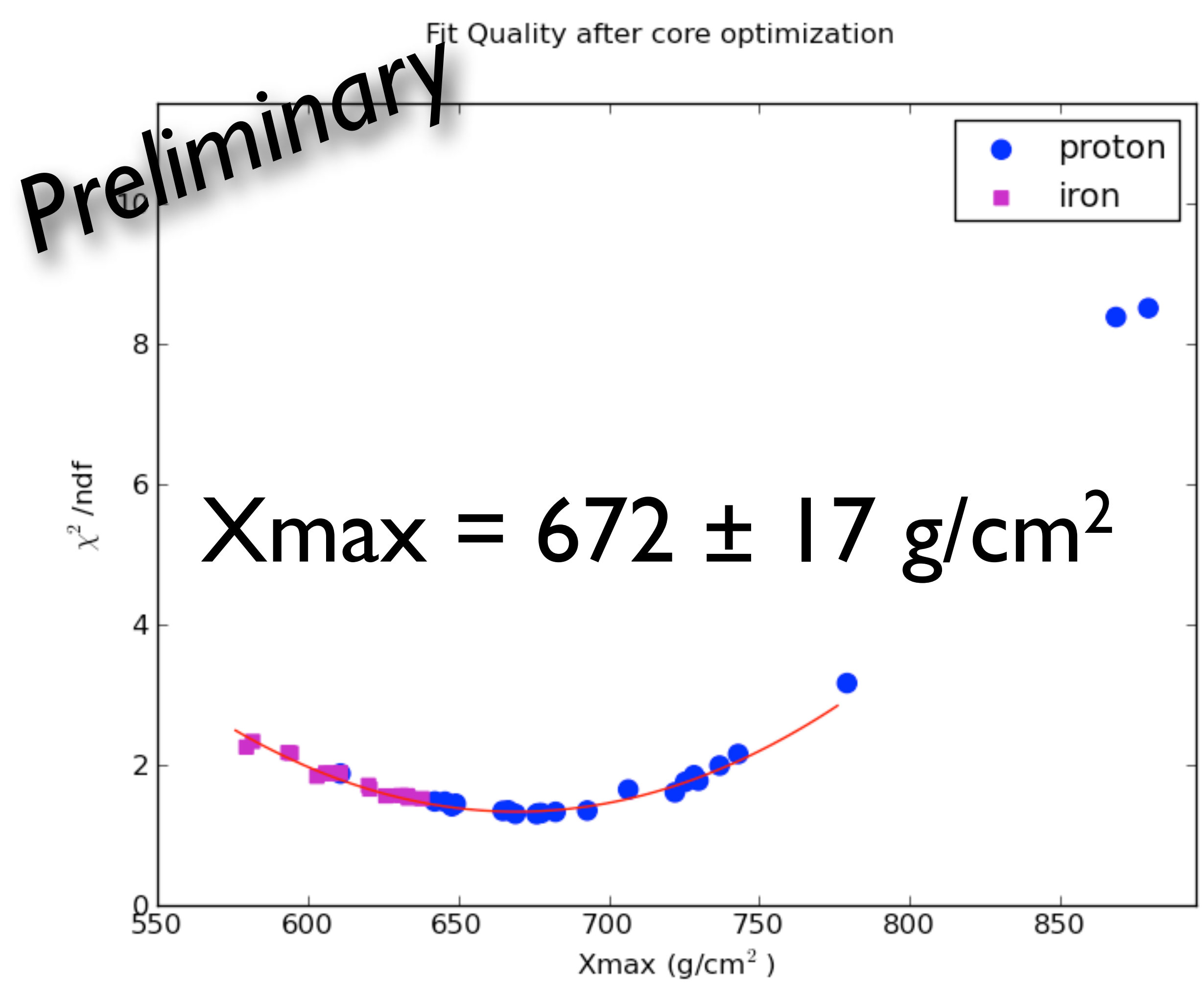
other systematic effects under investigation



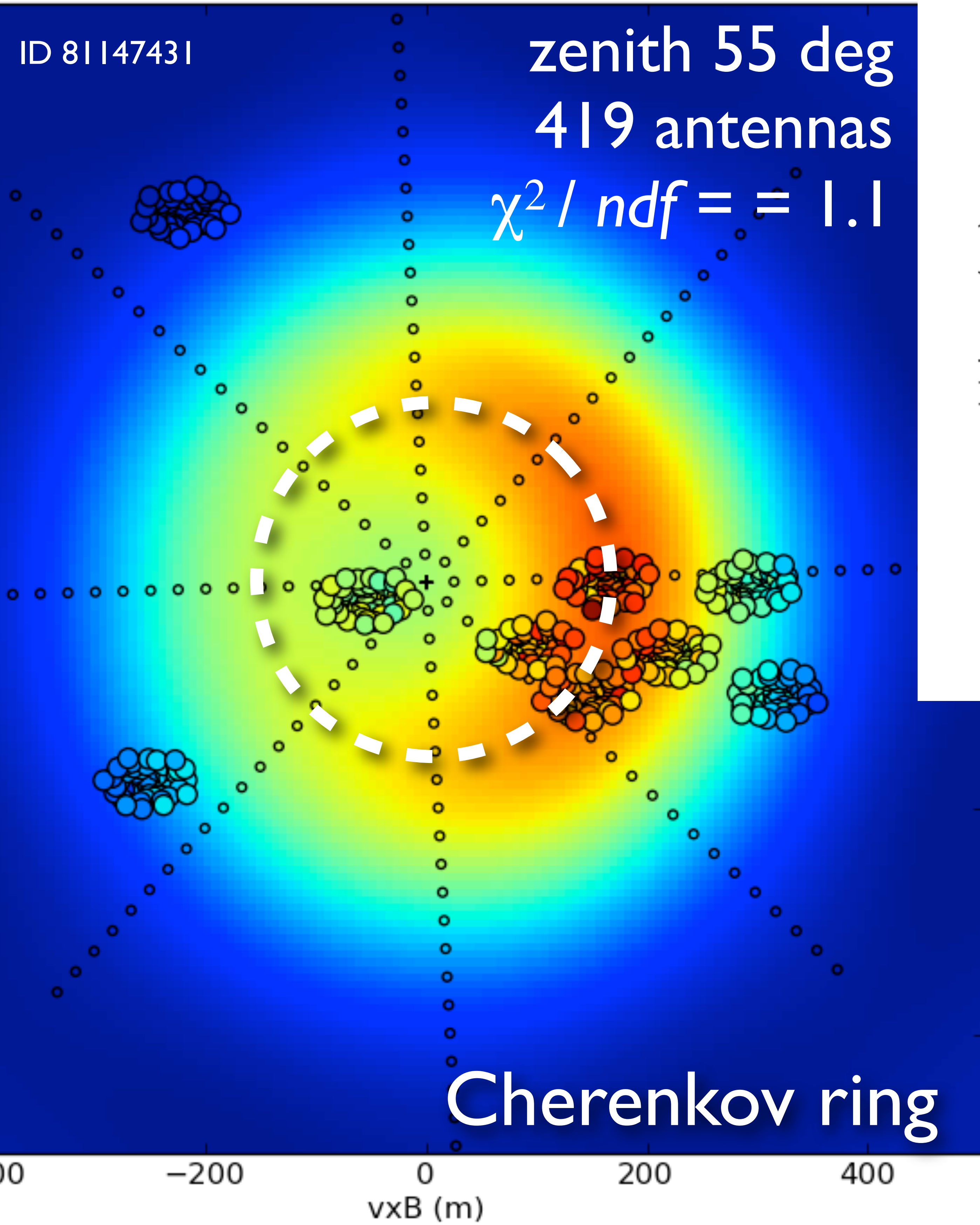
Radiation profile in shower plane
ID 63246771
zenith 17.5 deg
190 antennas
$\chi^2 / ndf = 1.3$
-200
−100
0
100
200
vxB (m)

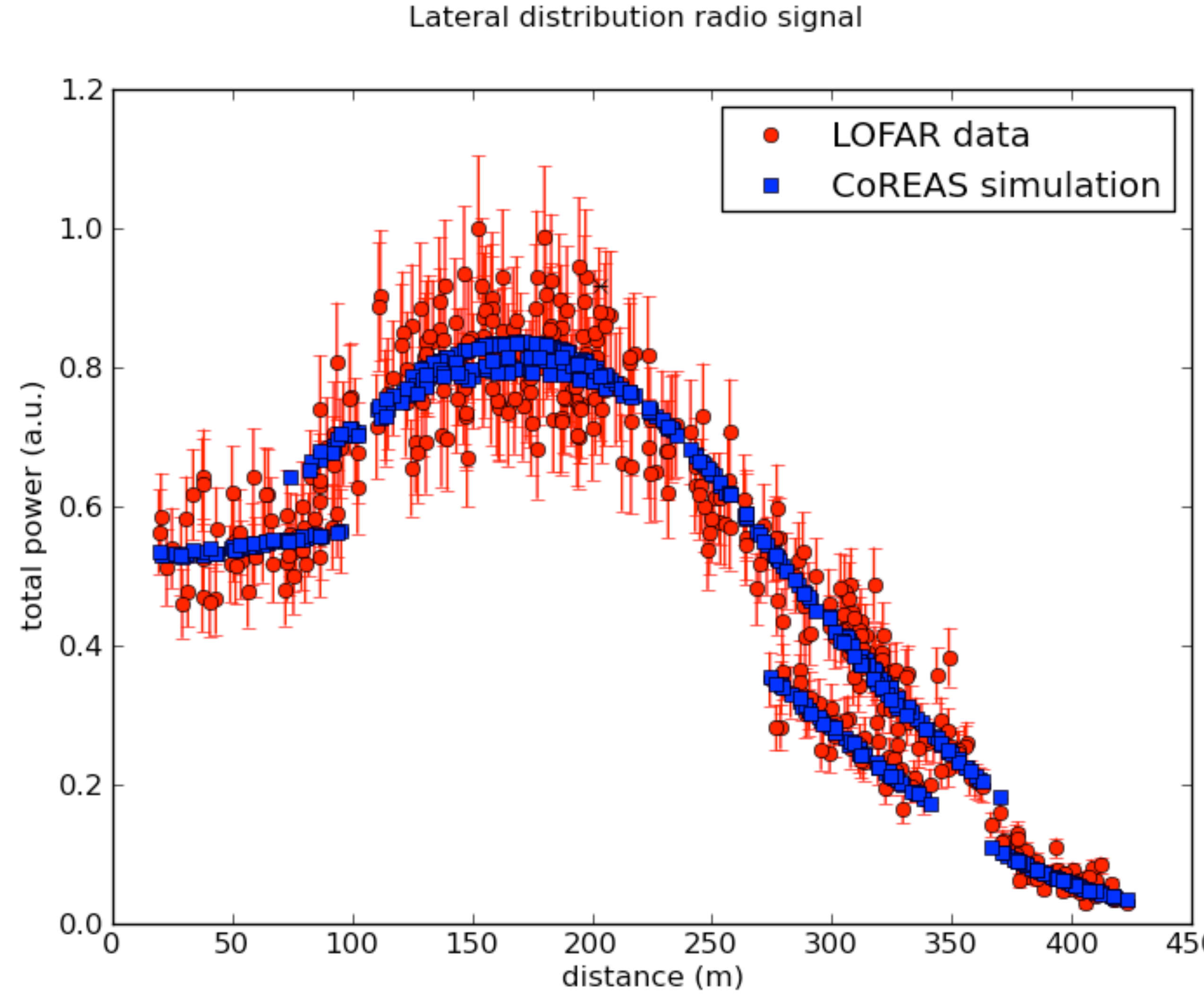


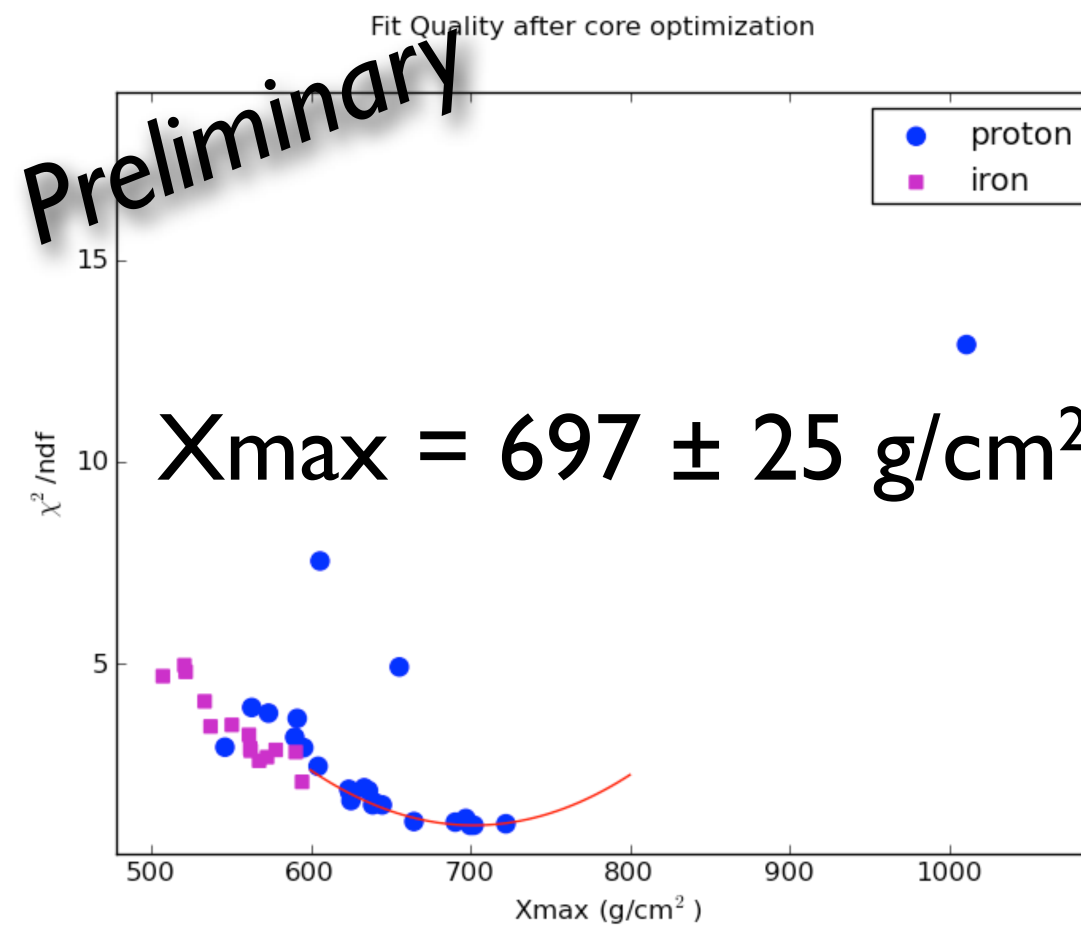
Lateral distribution radio signal
LOFAR data
CoREAS simulation
total power (a.u.)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
50
100
150
200
250
distance (m)



Fit Quality after core optimization
Preliminary
proton
iron
χ^2 /ndf
0
2
4
6
8
Xmax = 672 ± 17 g/cm²
550
600
650
700
750
800
850
Xmax (g/cm²)


ID 81147431
zenith 55 deg
419 antennas
$\chi^2 / ndf = = 1.1$
Cherenkov ring
−200
0
200
400
vxB (m)


Lateral distribution radio signal
LOFAR data
CoREAS simulation
total power (a.u.)
distance (m)


Fit Quality after core optimization
Preliminary
proton
iron
Xmax = 697 ± 25 g/cm²
χ^2 /ndf
Xmax (g/cm²)

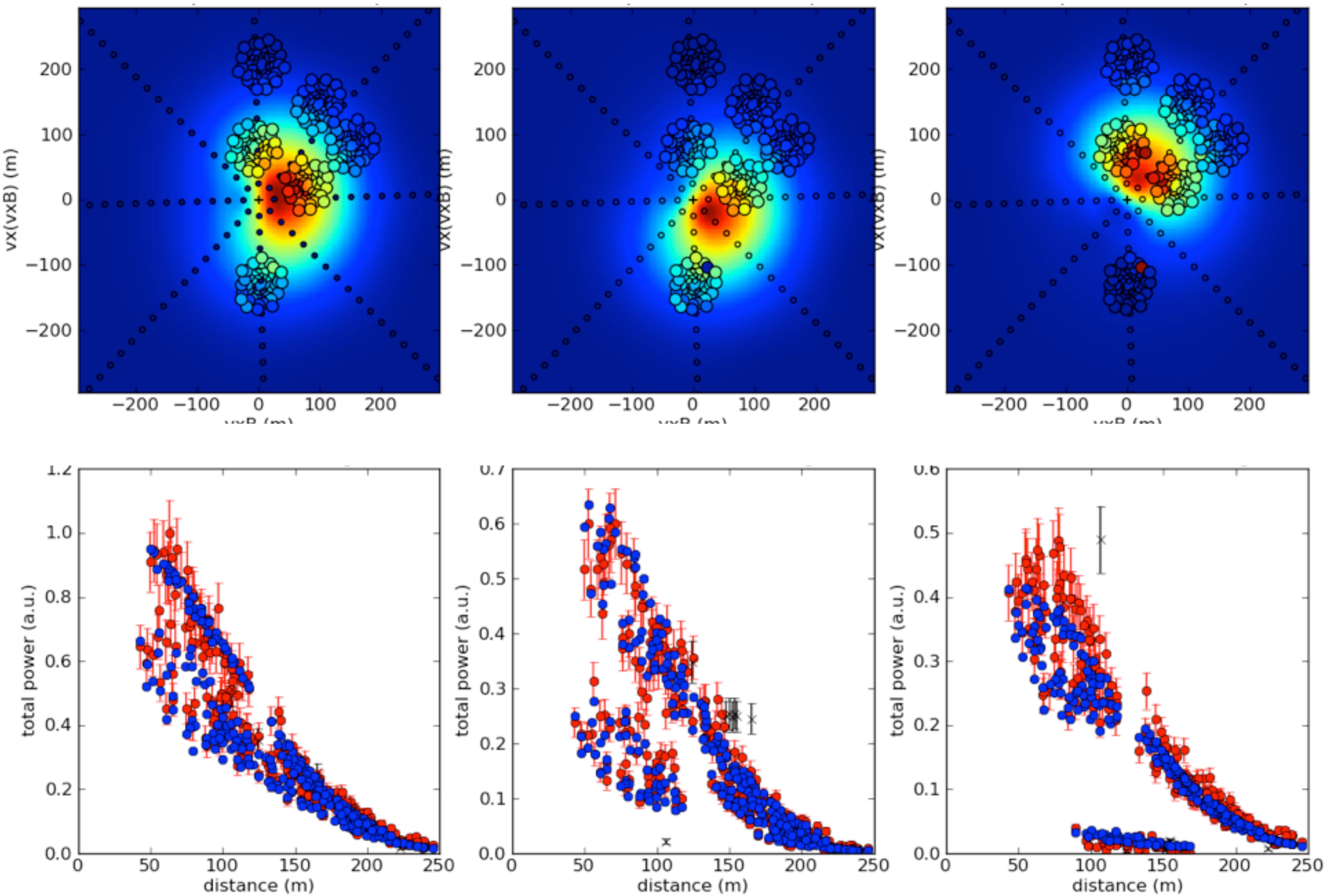
Conclusions

- **We understand air shower radio emission**
  - CoREAS sim in agreement with 300+ data point events!
  - geomagnetic, charge excess & Cherenkov observed
  - absolute power not yet available...
- **We can measure Xmax**
  - accurate reconstruction based on CoREAS sim $\sigma \sim 20$ g/cm^2
  - *coming*: independent analysis using wavefront shape
  - radio has duty cycle of near 100%
- **Future**
  - LOFAR composition energy range $10^{16.5}$ - $10^{18.5}$ eV
  - TUNKA-REX comparison with air-Cherenkov
  - AERA (Auger) comparison with FD & composition at highest energies

research funded by ERC Advanced Grant (H. Falcke) & NWO Veni Grant (S. Buitink)

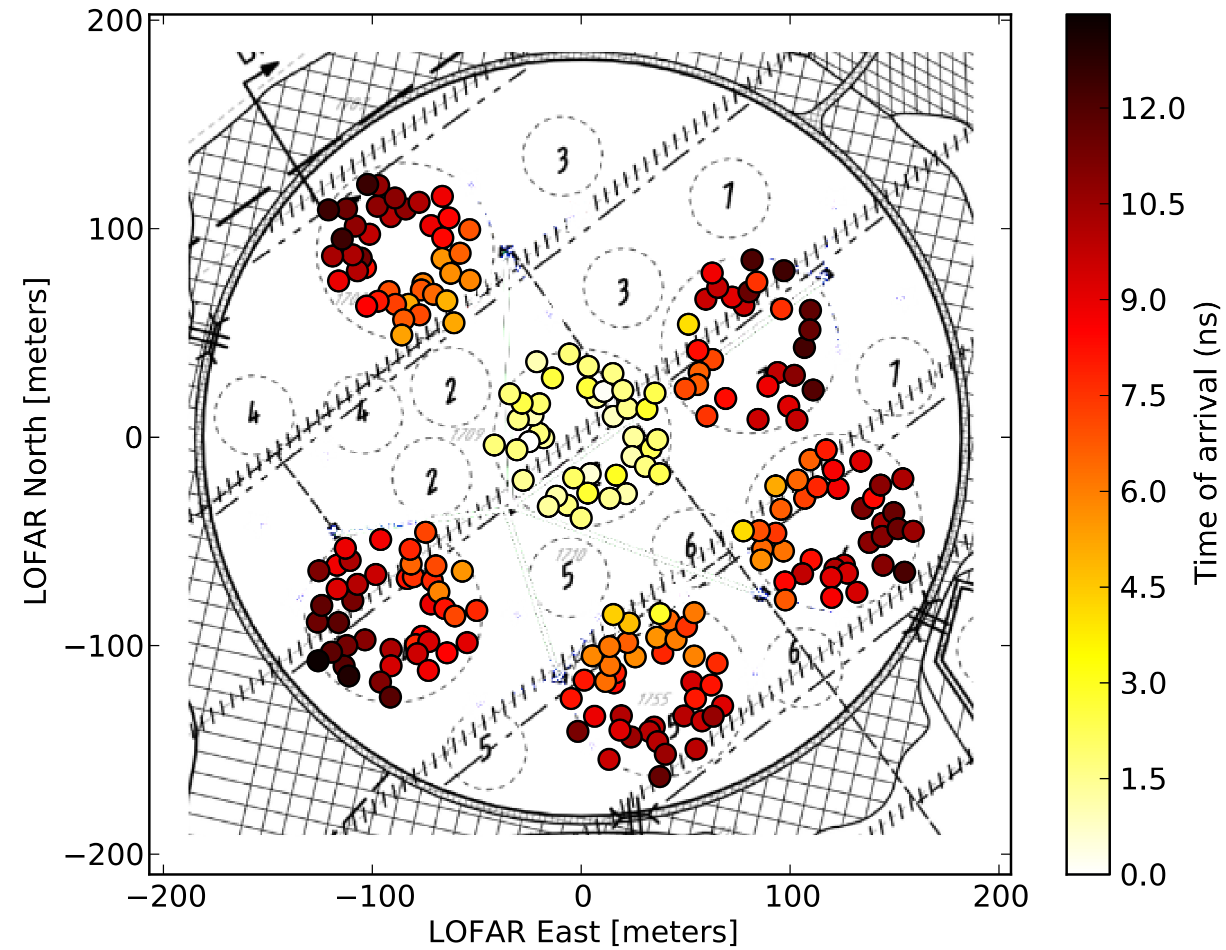
backup slides

polarization

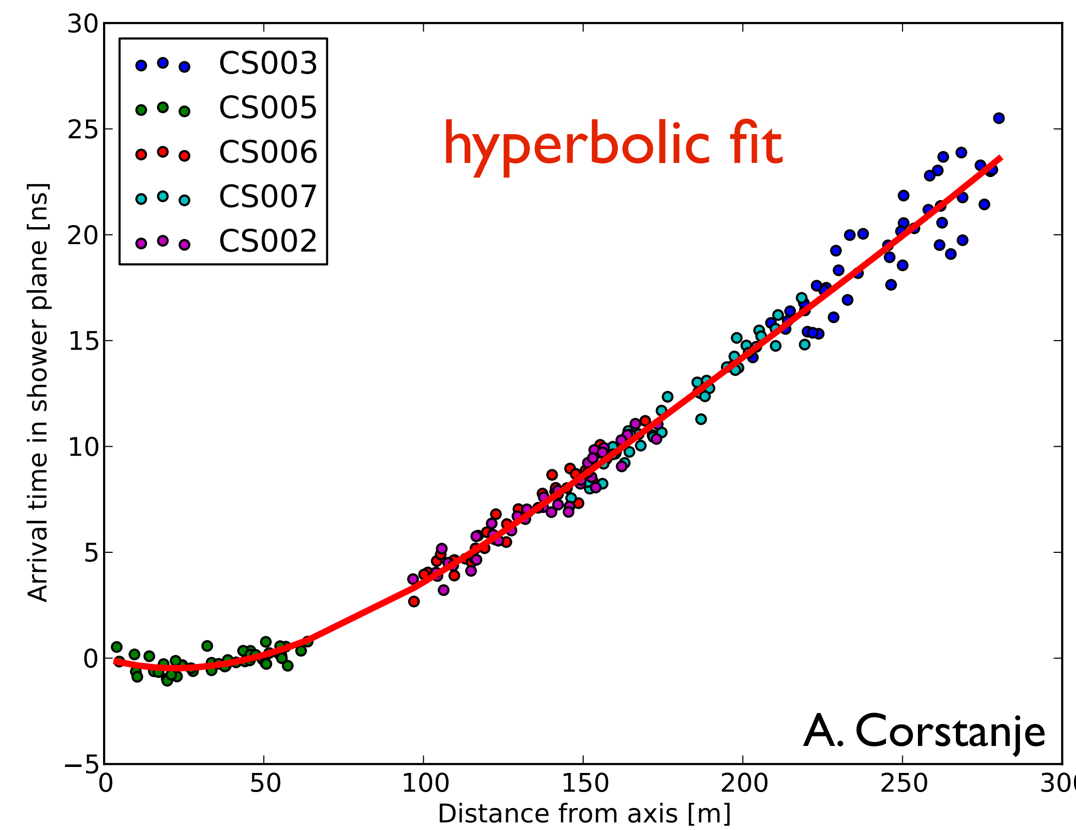


Total power X-dipole Y-dipole

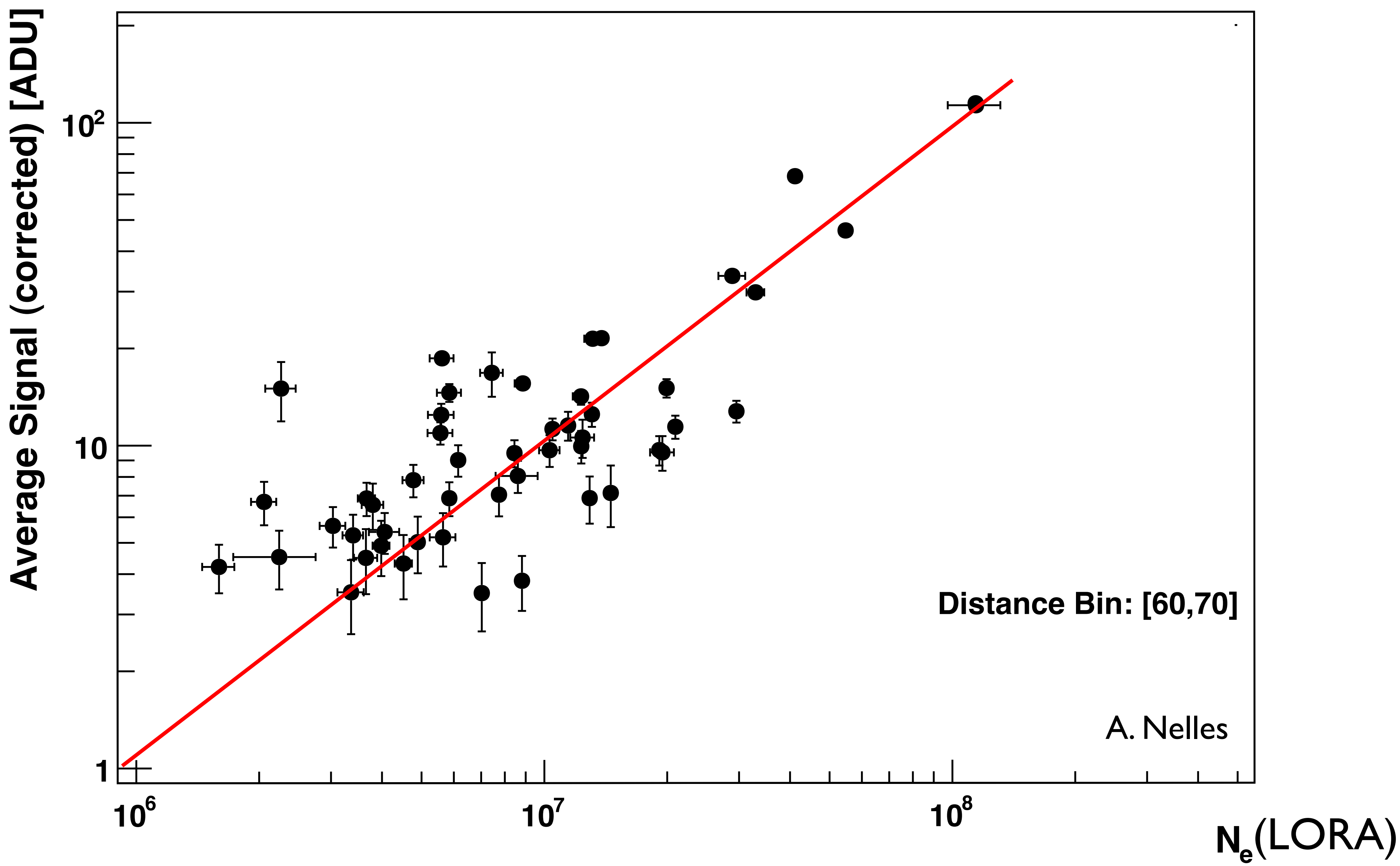
delays w.r.t. plane wave



- <u>Wavefront curvature</u> nanosecond precision (sub-sample!)
- not purely spherical or conical
- sensitive to Xmax (analysis ongoing)



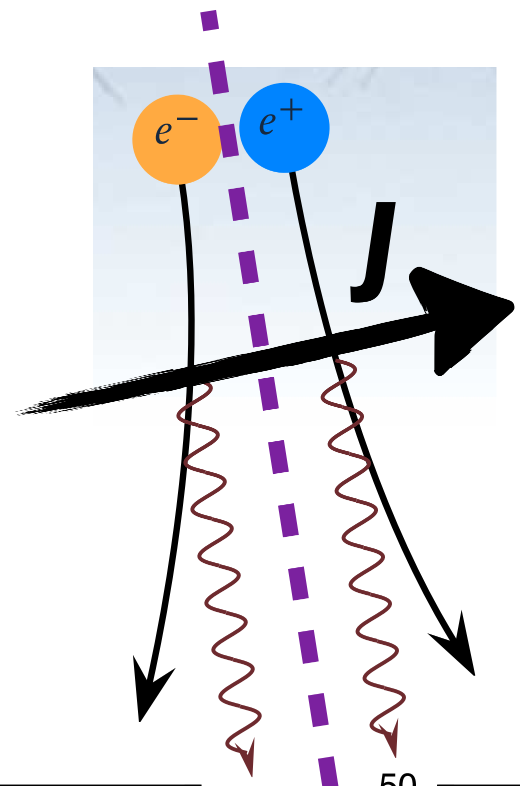
Energy Calibration



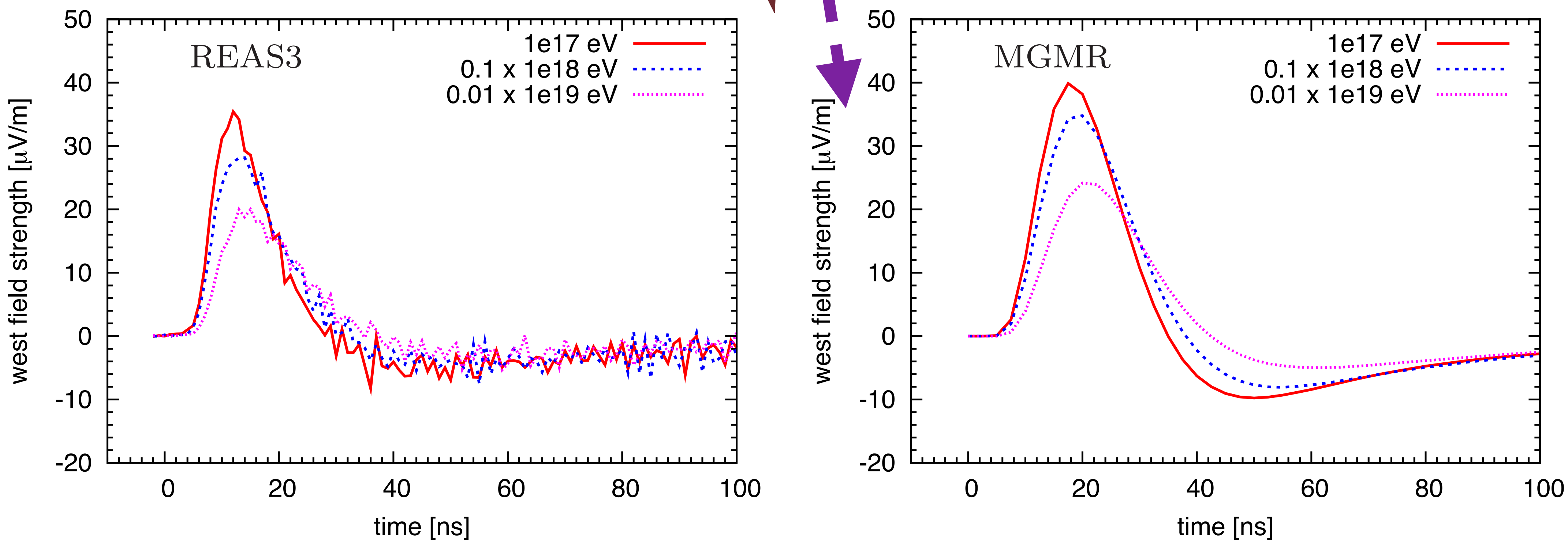
- signal strength at 60-70m axis distance
- coherent signal $P \sim n^2$
- spread due to shower-to-shower fluctuations

radio emission: converging models

<u>*microscopic:*</u>
geosynchrotron +
\`endpoint' radiation



<u>*macroscopic:*</u>
time-dependent
current densities
E ~ dJ/dt ~ dN/dt

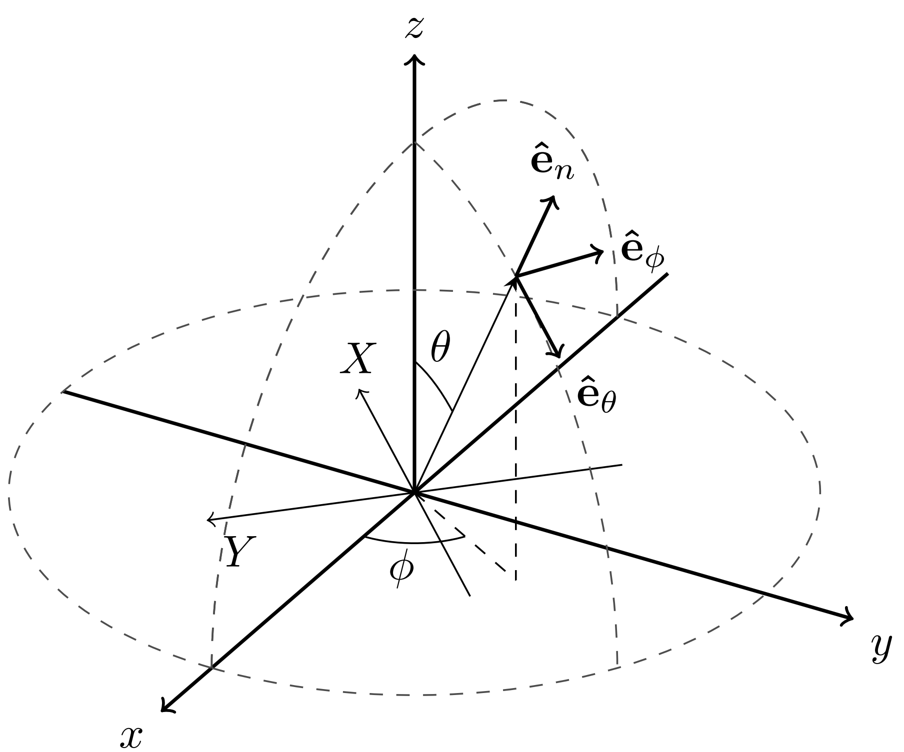


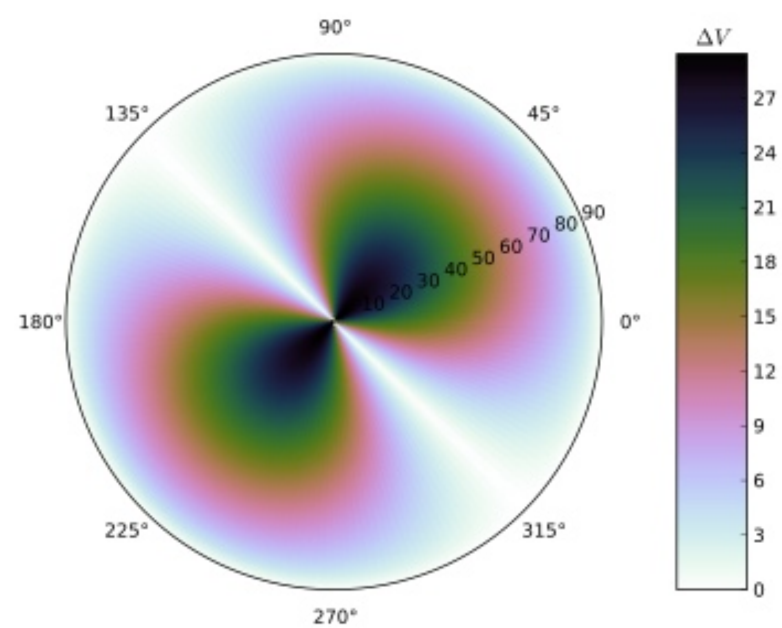
Huege, Ludwig Scholten, De Vries NIMPA 662 (2012) 179

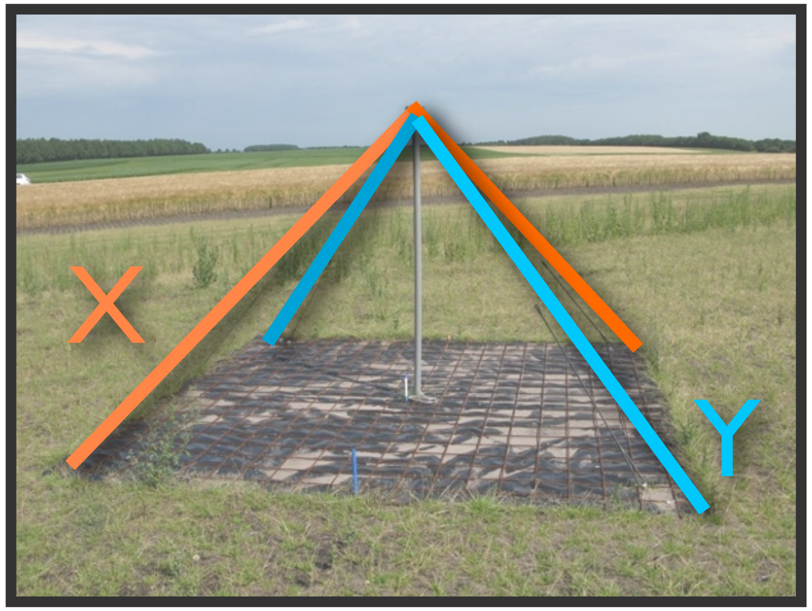
Now available: CoREAS, ZHAireS, EVA, Selfas
all include geomagnetic, charge excess, cherenkov effects

simulations

- CORSIKA 6.990 QGSJETII-03 + FLUKA
- CoREAS v0.9 T. Huege et al. AIPC 1535, 128 (2013)







raw sim pulses (xyz)

antenna simulation (incl. 30-80 MHz filt.)

power in X/Y dipole